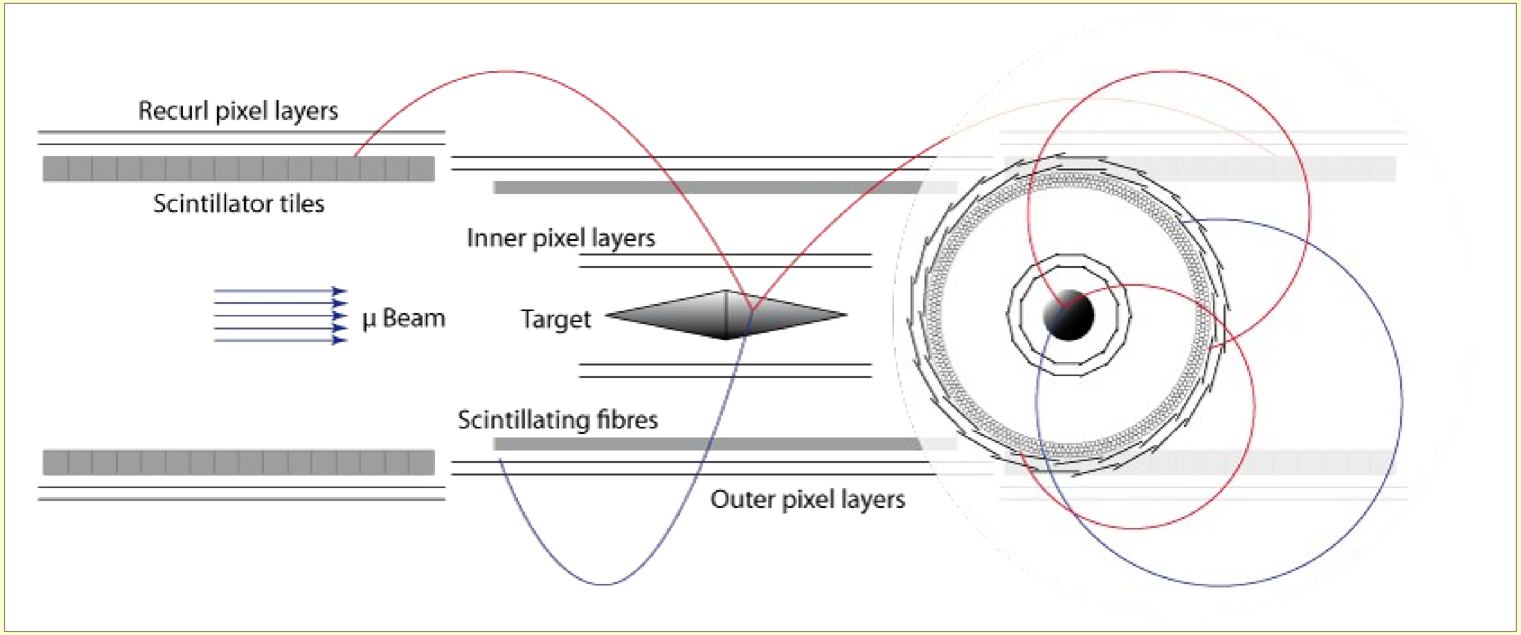
New Experimental Search for μ→eee

Paul Scherrer Institut

Open Users Meeting BV44

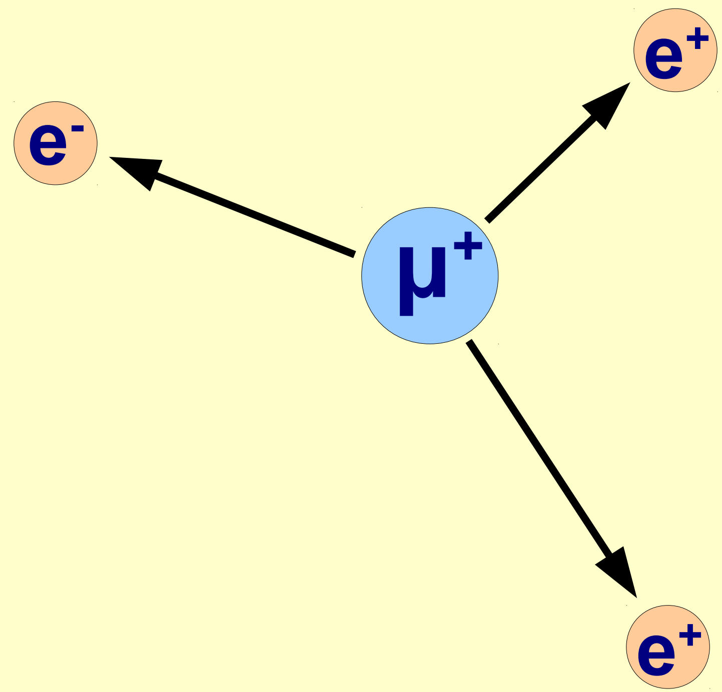
January 16, 2013

André Schöning for the **Mu3e Collaboration**



Experimental Goal

search for the LFV decay:



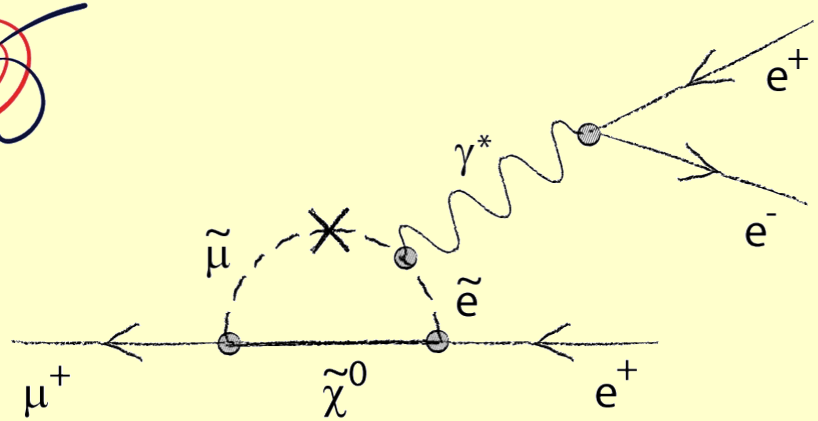
$$\mu^+ \rightarrow e^+e^+e^-$$

with a sensitivity of: $B(\mu^+ \rightarrow e^+e^+e^-) \leq 10^{-16}$

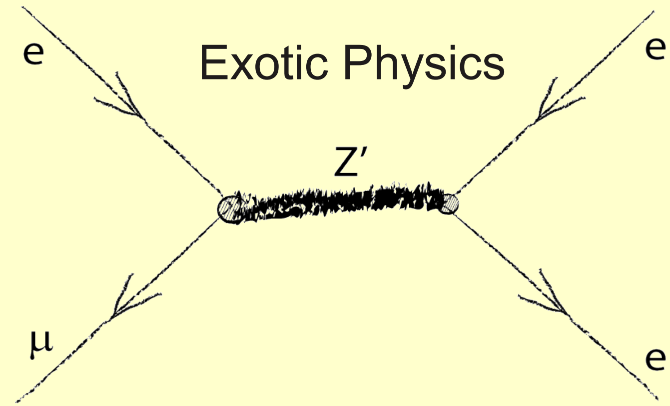
$\tau_{(\mu\rightarrow eee)} \geq 700$ **years** $(\tau_\mu = 2.2\ \mu s)$

predicted by SM: $B(\mu^+ \rightarrow e^+e^+e^-) << 10^{-50}$

Lepton Flavor Violating Decay: $\mu^+ \rightarrow e^+e^+e^-$



loop diagrams



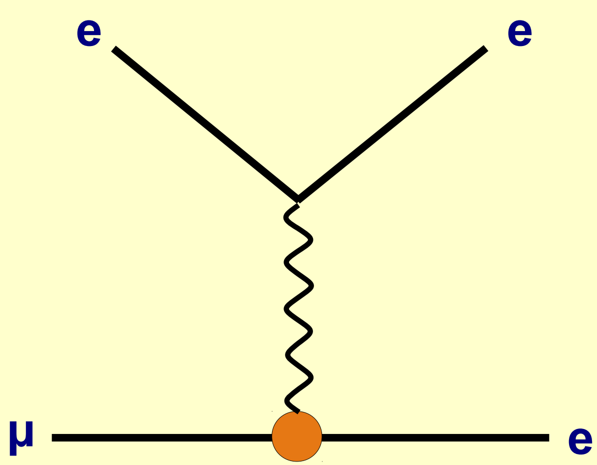
tree diagram

- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**

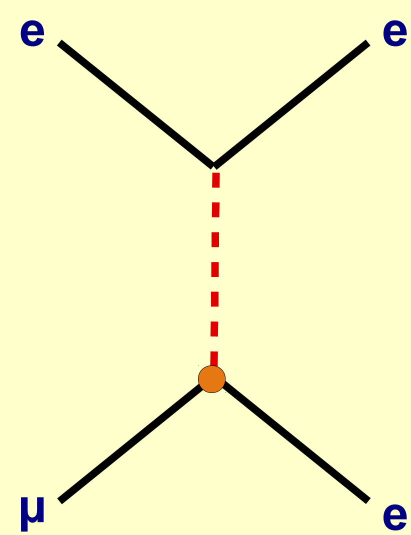
- **Higgs Triplet Model**
- **New Heavy Vector bosons (Z')**
- **Extra Dimensions (KK towers)**

Motivation $\mu^+ \to e^+e^+e^-$

$\mu^+ \to e^+e^+e^-$

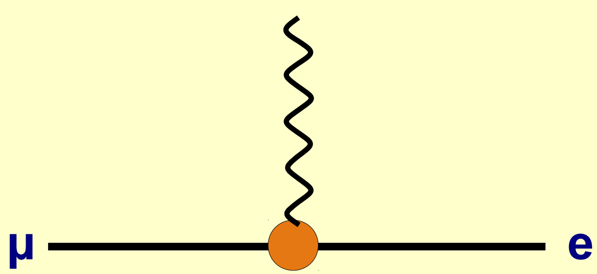


photon penguin



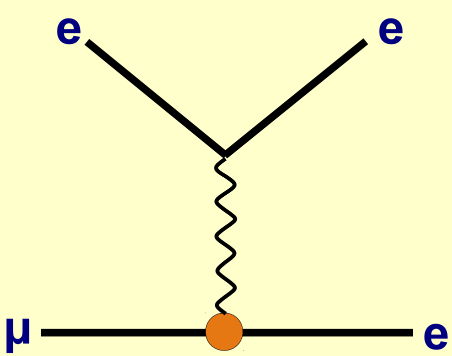
new LFV mediator

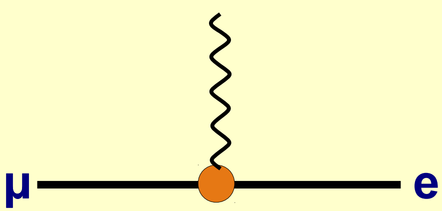
$\mu^+ \to e^+\gamma$



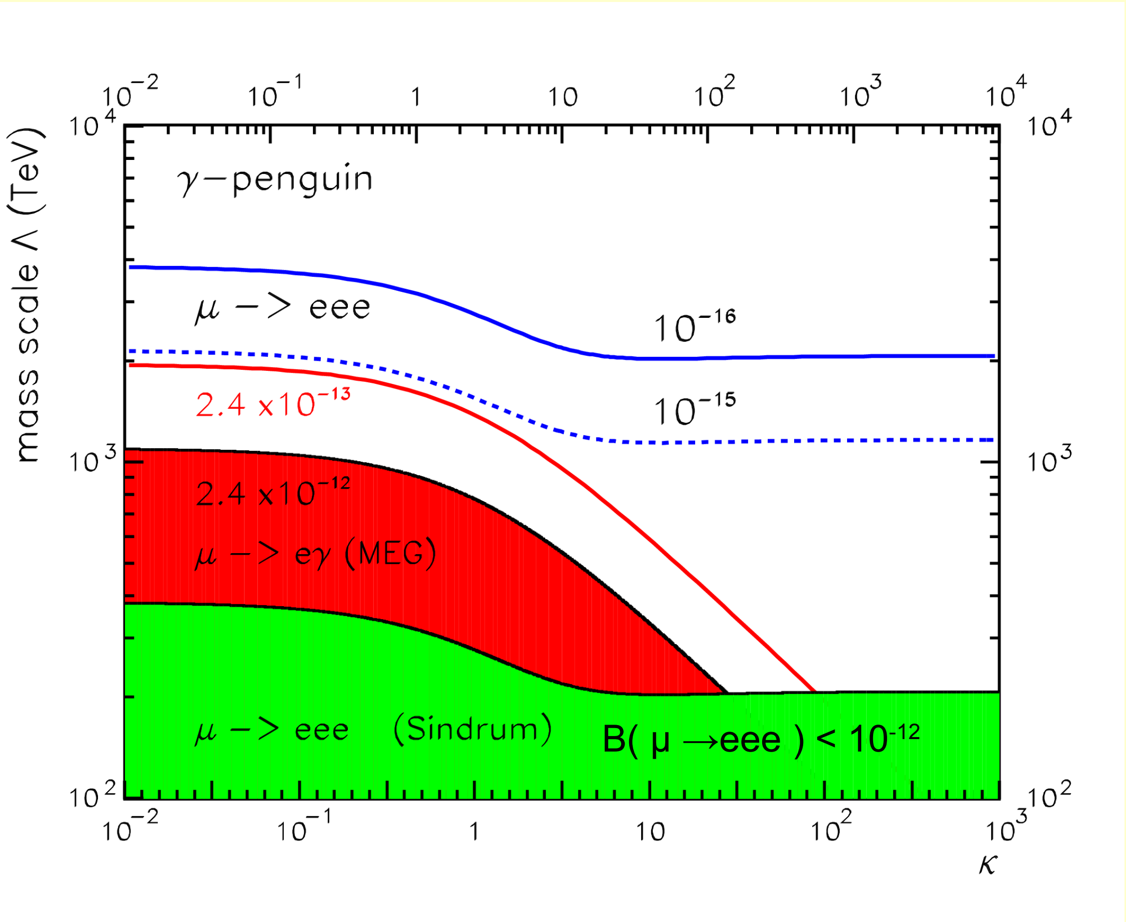
photon penguin

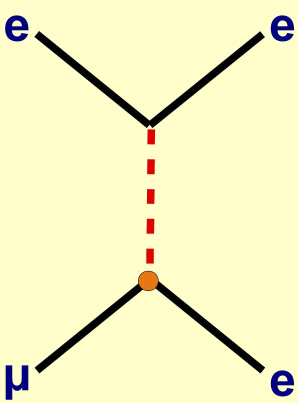
Model Independent Comparison





$\kappa \rightarrow 0$





$\kappa \rightarrow \infty$

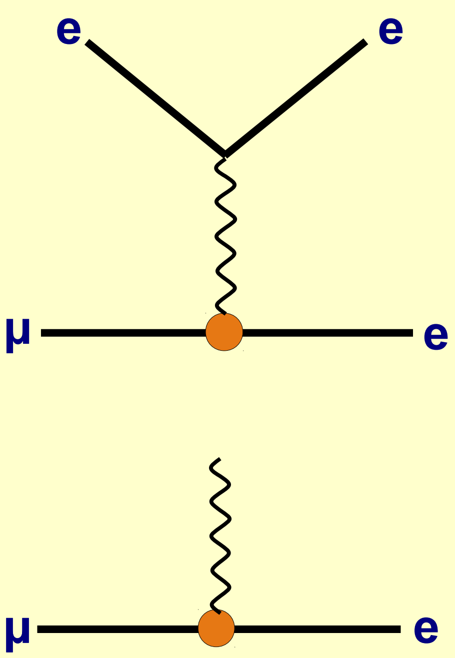
Effective cLFV Lagrangian:

$$L = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\nu^{e\mu} J^{\nu, ee}$$

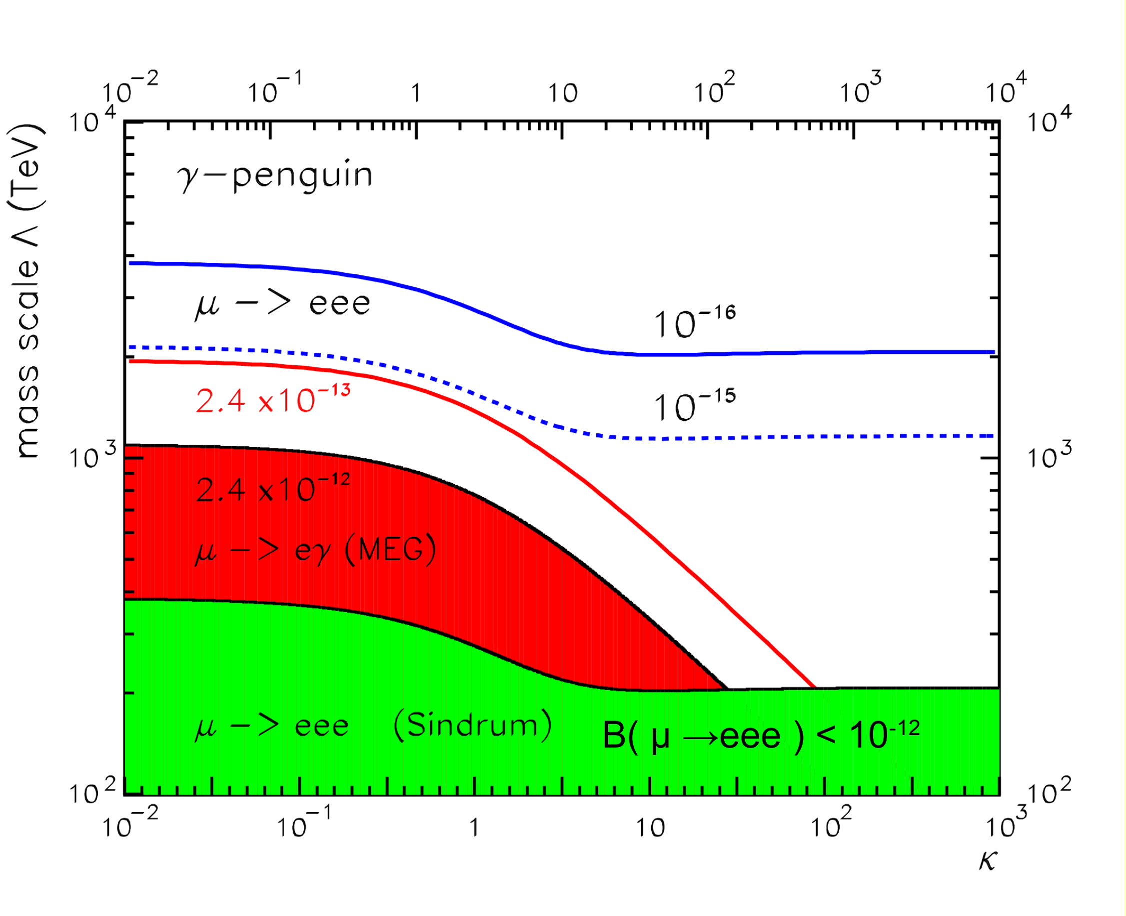
κ = parameter

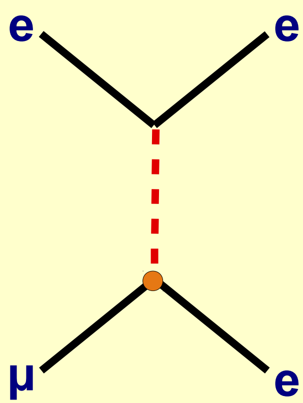
Λ = common effective mass scale

Model Independent Comparison



$\kappa \rightarrow 0$





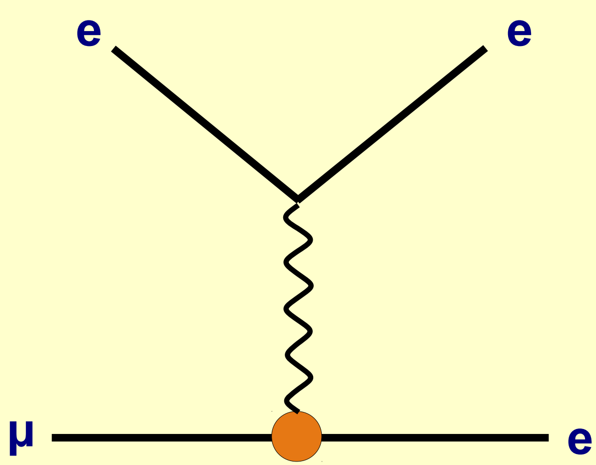
$\kappa \rightarrow \infty$

$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \sim 0.006$$

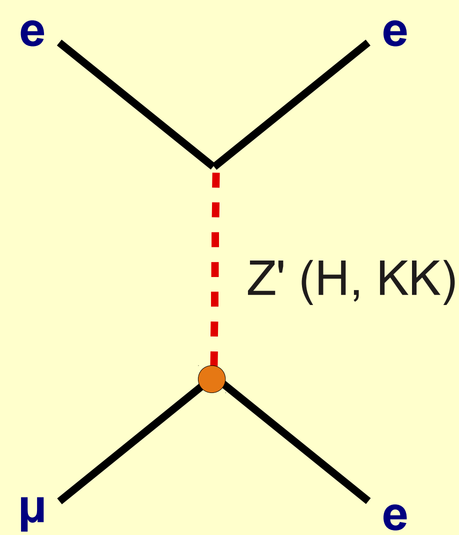
$$\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} = \infty$$

The $\mu^+ \rightarrow e^+e^+e^-$ Tree Diagram

$\mu^+ \rightarrow e^+e^+e^-$

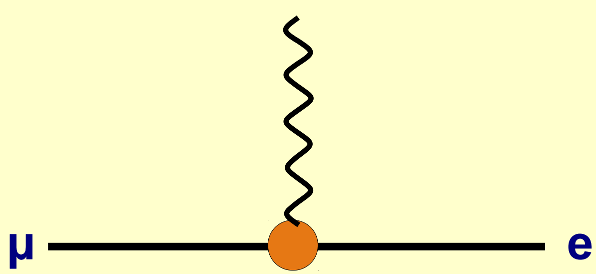


photon penguin



new LFV mediator

$\mu^+ \rightarrow e^+\gamma$



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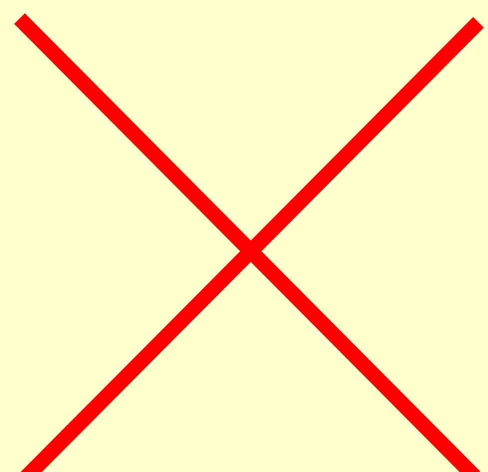
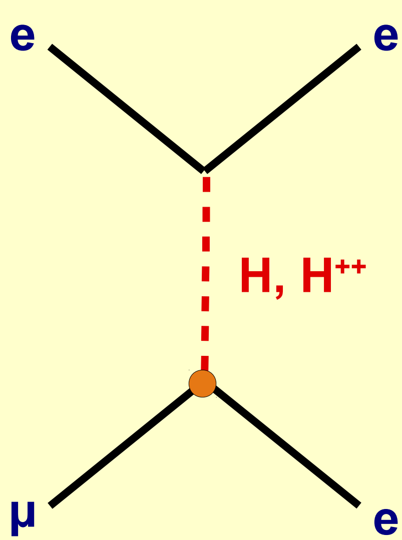


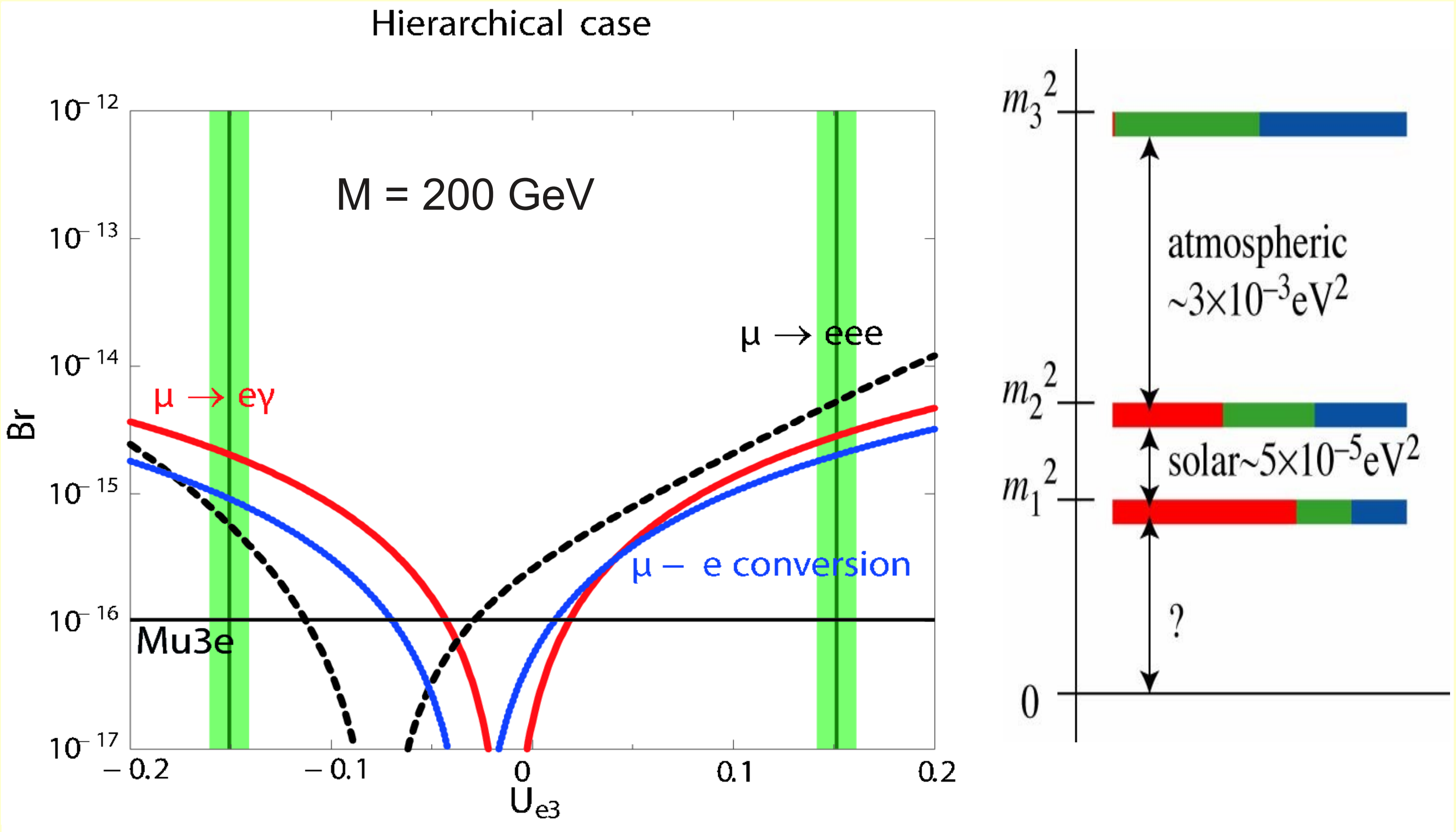
Example: Higgs Triplet Models

M.Kakizaki et al., Phys.Lett. **B566** 210, 2003

- Motivated by Left-Right Symmetric Models



triplet Higgs

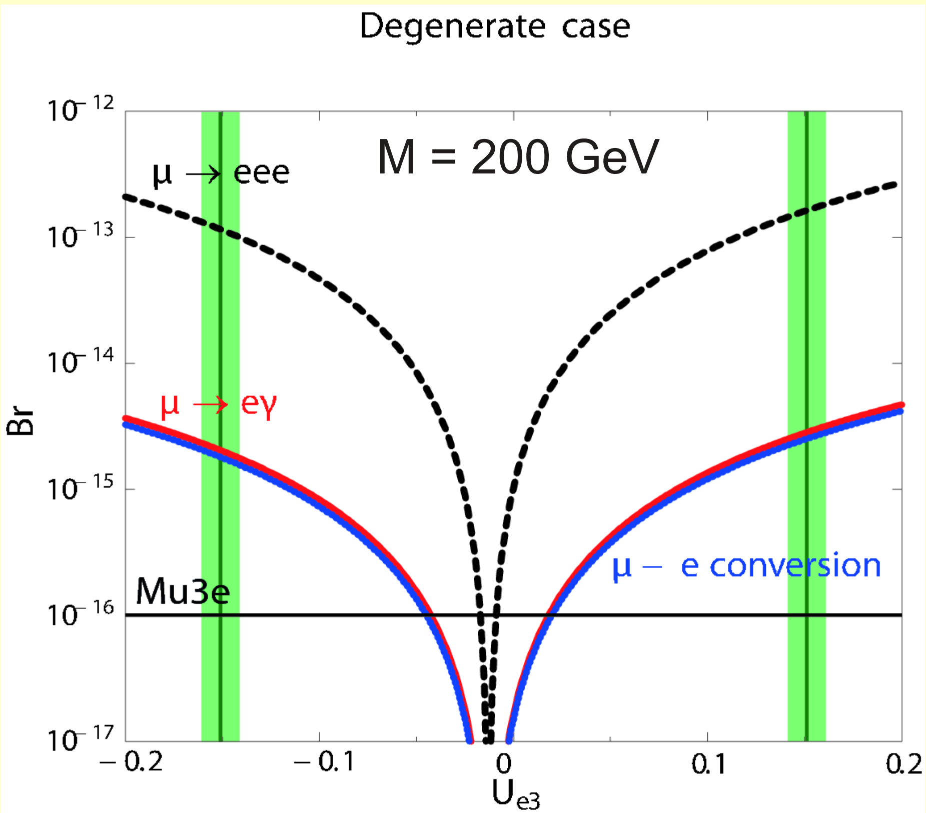


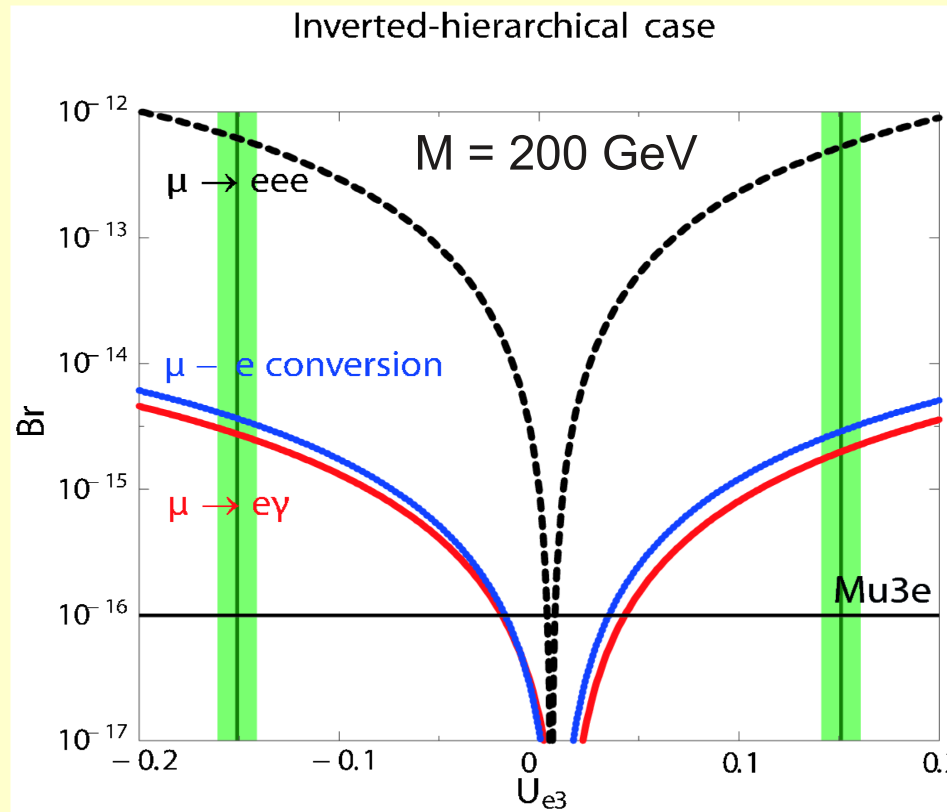
related to neutrino masses (→ ν mass pattern)

Example: Higgs Triplet Models II

M.Kakizaki et al., Phys.Lett. **B566** 210, 2003

- Motivated by Left-Right Symmetric Models



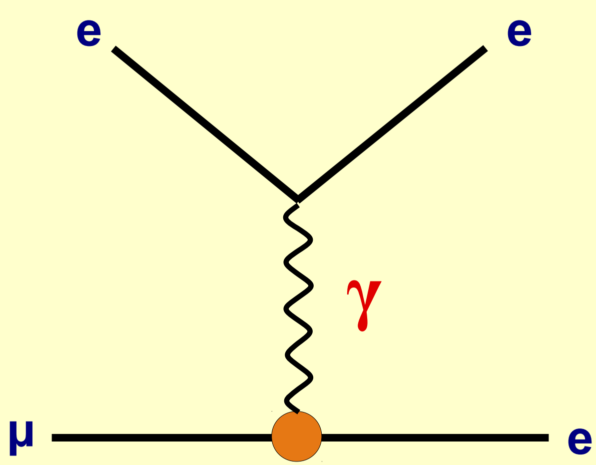


$$Br \propto \frac{A^4}{M^4}$$

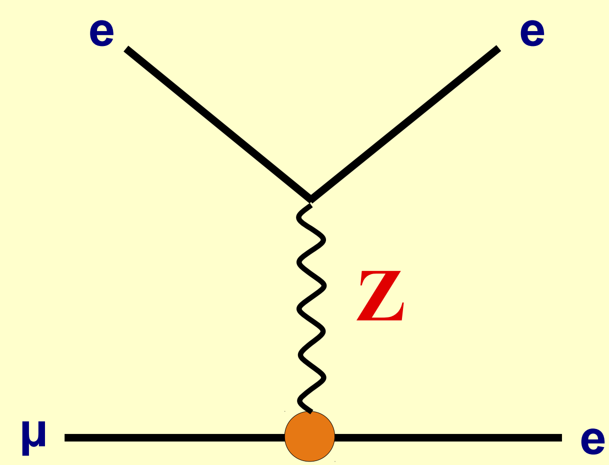
A= trilinear coupling (25 eV)

The $\mu^+ \rightarrow e^+e^+e^-$ Z-Penguin Diagram

$\mu^+ \rightarrow e^+e^+e^-$

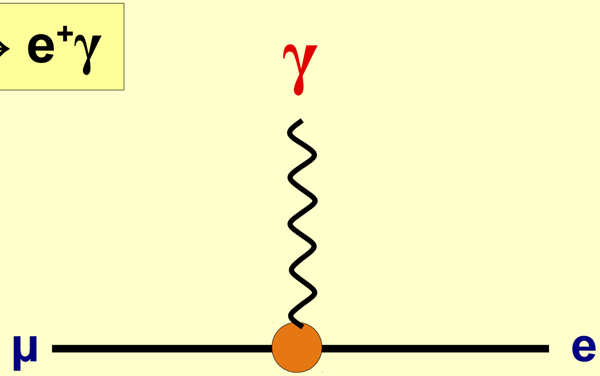


photon penguin

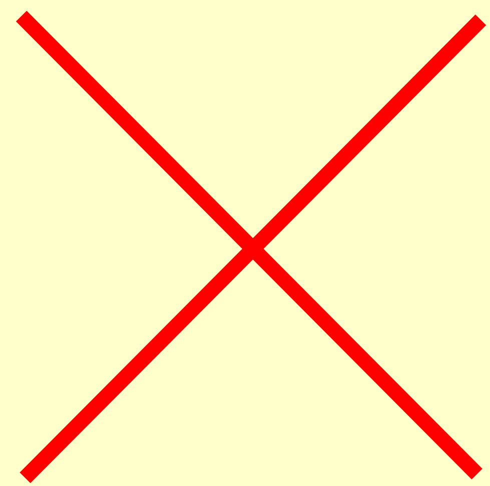


Z - penguin

$\mu^+ \rightarrow e^+\gamma$

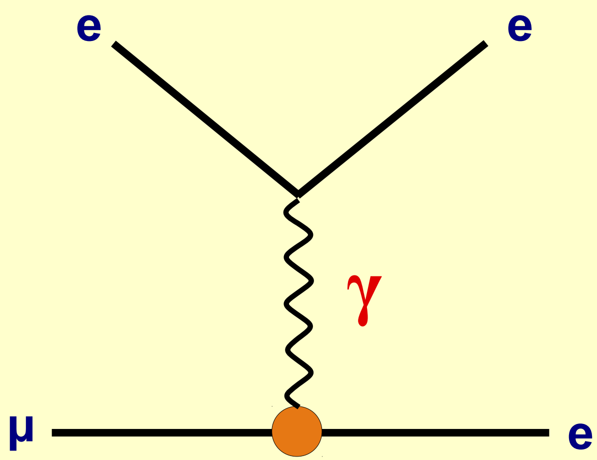


photon penguin

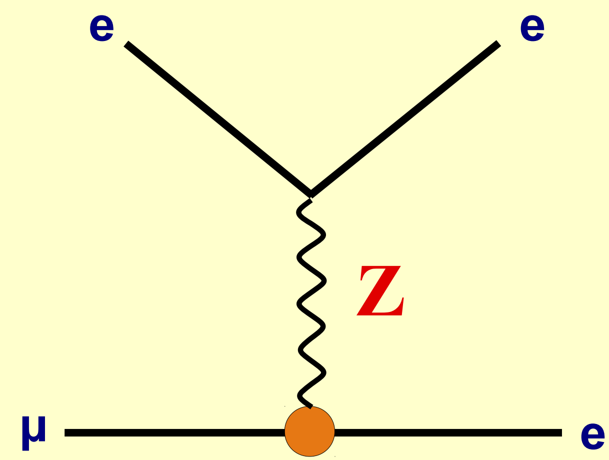


The $\mu^+ \rightarrow e^+e^+e^-$ Z-Penguin Diagram

$\mu^+ \rightarrow e^+e^+e^-$



photon penguin



Z - penguin

from dimensional analysis:

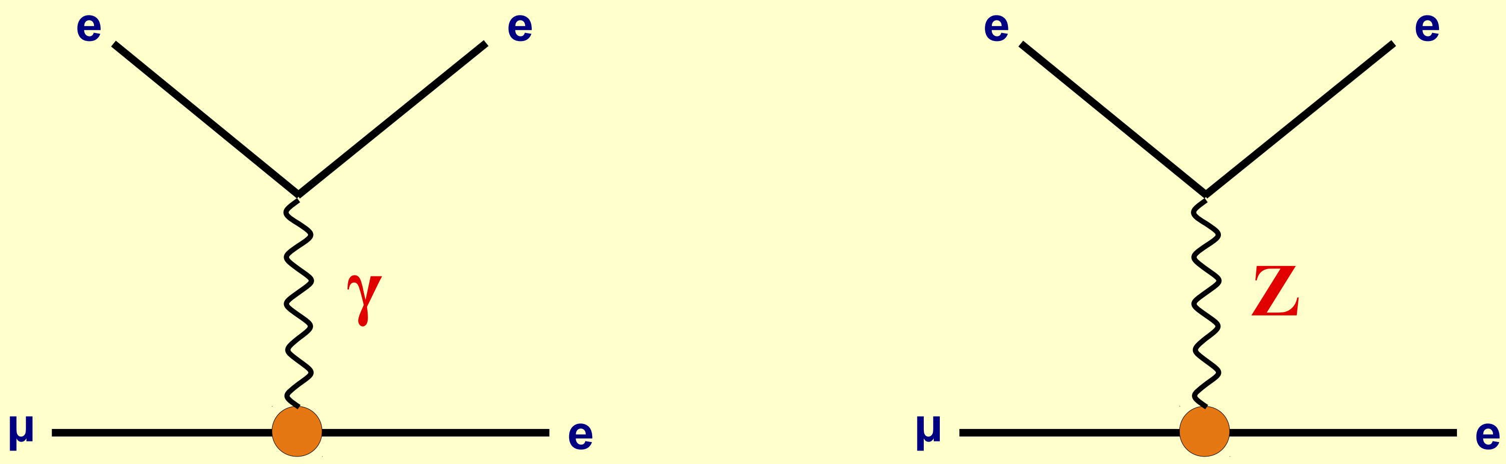
$$Br \propto \frac{m_\mu^5}{\Lambda^4}$$

$$Br \propto \frac{m_\mu^5}{m_Z^4} f\left(\Lambda^4\right)$$

dominates if $\Lambda >> m_Z$

The $\mu^+ \rightarrow e^+e^+e^-$ Z-Penguin Diagram

$\mu^+ \rightarrow e^+e^+e^-$



photon penguin

Z - penguin

from dimensional analysis:

$$Br \propto \frac{m_\mu^5}{\Lambda^4}$$

$$Br \propto \frac{m_\mu^5}{m_Z^4} f\left(\Lambda^4\right)$$

no decoupling in many models!

Many Recent Papers on/with Z-penguin

Hirsch et al., ***Enhancing $l_i \rightarrow 3l_j$ with the Z^0-penguin*** **[arXiv:1202.1825]**

X Hirsch et al., *Phenomenology of the* ***minimal supersymmetric $U(1)_{B-L} \times U(1)_R$*** *extension of the standard model* [arXiv:1206.3516]

del Aguila et al., *Lepton flavor violation in the Simplest* ***Little Higgs*** *model* [arXiv:1101.2936]

Dreiner at al., *New bounds on trilinear* ***R-parity*** *violation from lepton flavor violating observables* [arXiv:1204.5925]

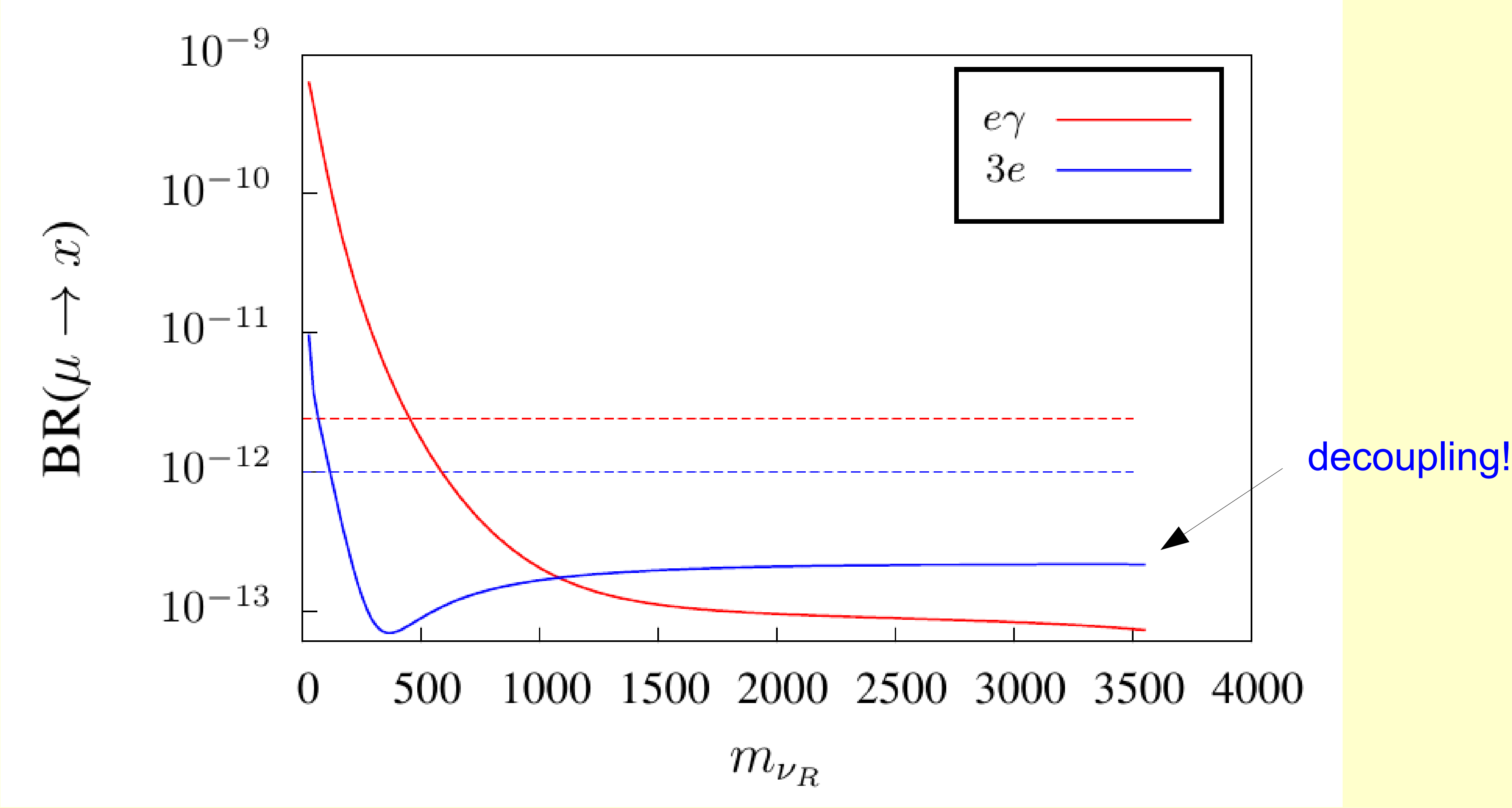
X Abada et al., *Enhancing lepton flavour violation in the* ***supersymmetric inverse seesaw*** *beyond the dipole contribution* [arXiv:1206.6497]

Ilakovac et al., *Charged Lepton Flavour Violation in Supersymmetric* ***Low-Scale Seesaw*** *Models* [arXiv:1212.5939]

Aristizabal Sierra et al., *Minimal lepton flavor violating realizations of* ***minimal seesaw*** *models* [arXiv:1205.5547]

<u>Hirsch et al.</u>, *Phenomenology of the minimal supersymmetric $U(1)_{B-L} \times U(1)_R$ extension of the standard model* [arXiv:1206.3516]

MSSM Model with heavy right-handed neutrino and Z'



m_0 = 800 GeV, $M_{1/2}$ = 1200 GeV, tan β = 10, A_0 = 0
v_R = 10 TeV, tan β_R = 1.05, μ_R = −500 GeV, m_{AR} = 1000 GeV.

Supersymmetric Seesaw Mechanism

Hisana et al., hep-ph/9510309

$$\Gamma(l_j^- \to l_i^- \; l_i^- \; l_i^+) = \frac{e^4}{512\pi^3} m_{l_j}^5 \Big[|A_1^L|^2 + |A_1^R|^2 - 2(A_1^L A_2^{R*} + A_2^L A_1^{R*} + h.c.)$$

photon

$$+(|A_2^L|^2 + |A_2^R|^2) \left(\frac{16}{3} \ln \frac{m_{l_j}}{2m_{l_i}} - \frac{14}{9} \right)$$

$$+\frac{1}{6}(|B_1^L|^2 + |B_1^R|^2) + \frac{1}{3}(|B_2^L|^2 + |B_2^R|^2) + \frac{1}{24}(|B_3^L|^2 + |B_3^R|^2)$$

box diagrams

$$+6(|B_4^L|^2 + |B_4^R|^2) - \frac{1}{2}(B_3^L B_4^{L*} + B_3^R B_4^{R*} + h.c.)$$

$$+\frac{1}{3}(A_1^L B_1^{L*} + A_1^R B_1^{R*} + A_1^L B_2^{L*} + A_1^R B_2^{R*} + h.c.)$$

$$-\frac{2}{3}(A_2^R B_1^{L*} + A_2^L B_1^{R*} + A_2^L B_2^{R*} + A_2^R B_2^{L*} + h.c.)$$

Z-penguin

$$+\frac{1}{3}\Big\{ 2(|F_{LL}|^2 + |F_{RR}|^2) + |F_{LR}|^2 + |F_{RL}|^2$$

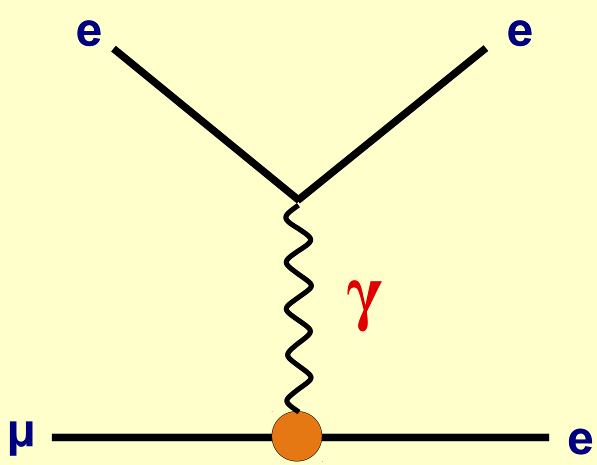
$$+(B_1^L F_{LL}^* + B_1^R F_{RR}^* + B_2^L F_{LR}^* + B_2^R F_{RL}^* + h.c.)$$

$$+2(A_1^L F_{LL}^* + A_1^R F_{RR}^* + h.c.) + (A_1^L F_{LR}^* + A_1^R F_{RL}^* + h.c.)$$

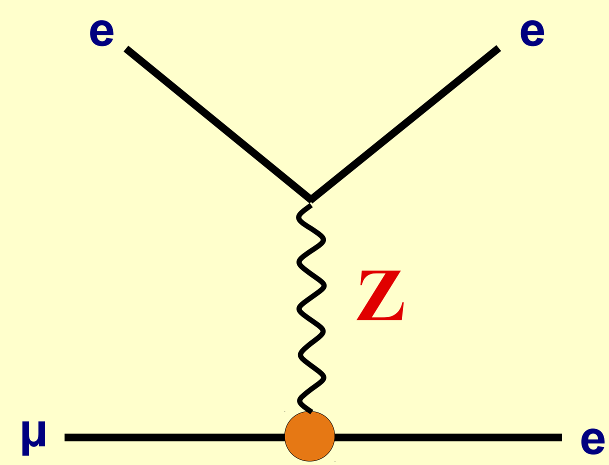
$$-4(A_2^R F_{LL}^* + A_2^L F_{RR}^* + h.c.) - 2(A_2^L F_{RL}^* + A_2^R F_{LR}^* + h.c.)\Big\}\Big],$$

Motivation $\mu^+ \rightarrow e^+e^+e^-$

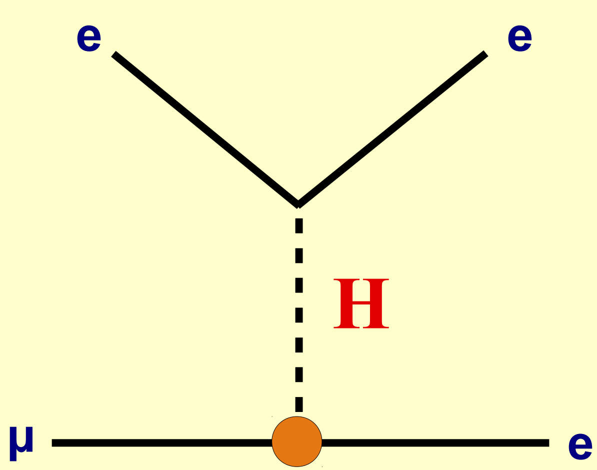
$\mu^+ \rightarrow e^+e^+e^-$



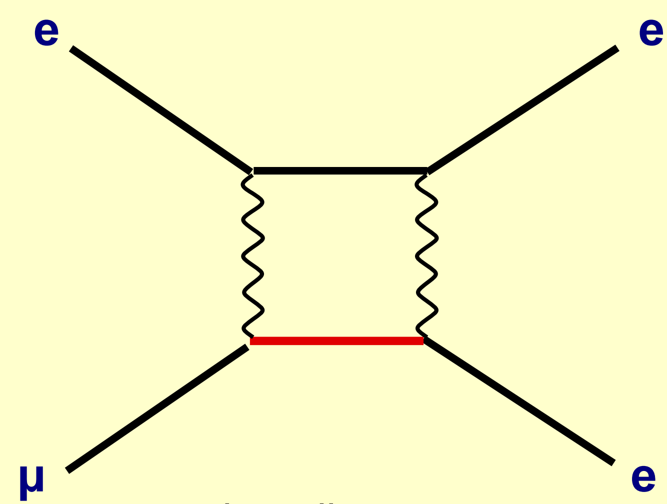
photon penguin



Z - penguin



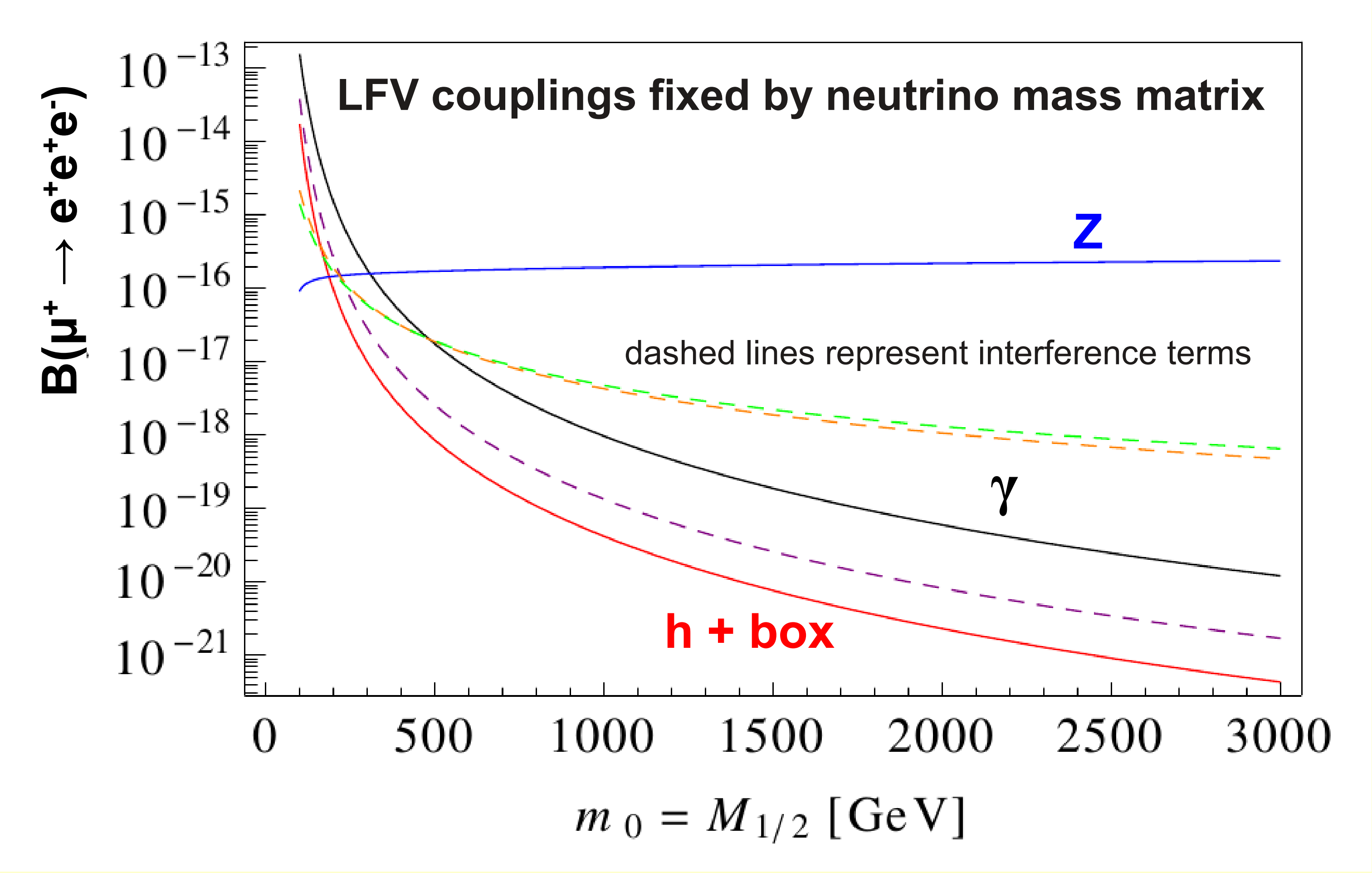
Higgs-penguin



box diagram

Abada et al., *Enhancing lepton flavour violation in the supersymmetric inverse seesaw beyond the dipole contribution* [arXiv:1206.6497]

Inverse Seesaw Model

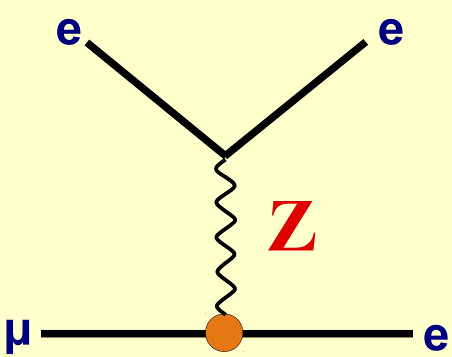


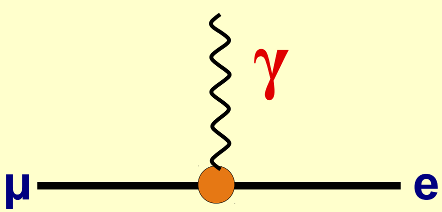
Non decoupling behaviour of Z-penguin contribution

Note $\mu^+ \to e^+e^+e^-$ dominates over $\mu^+ \to e^+ \gamma$ for $m_0 > 1$ TeV

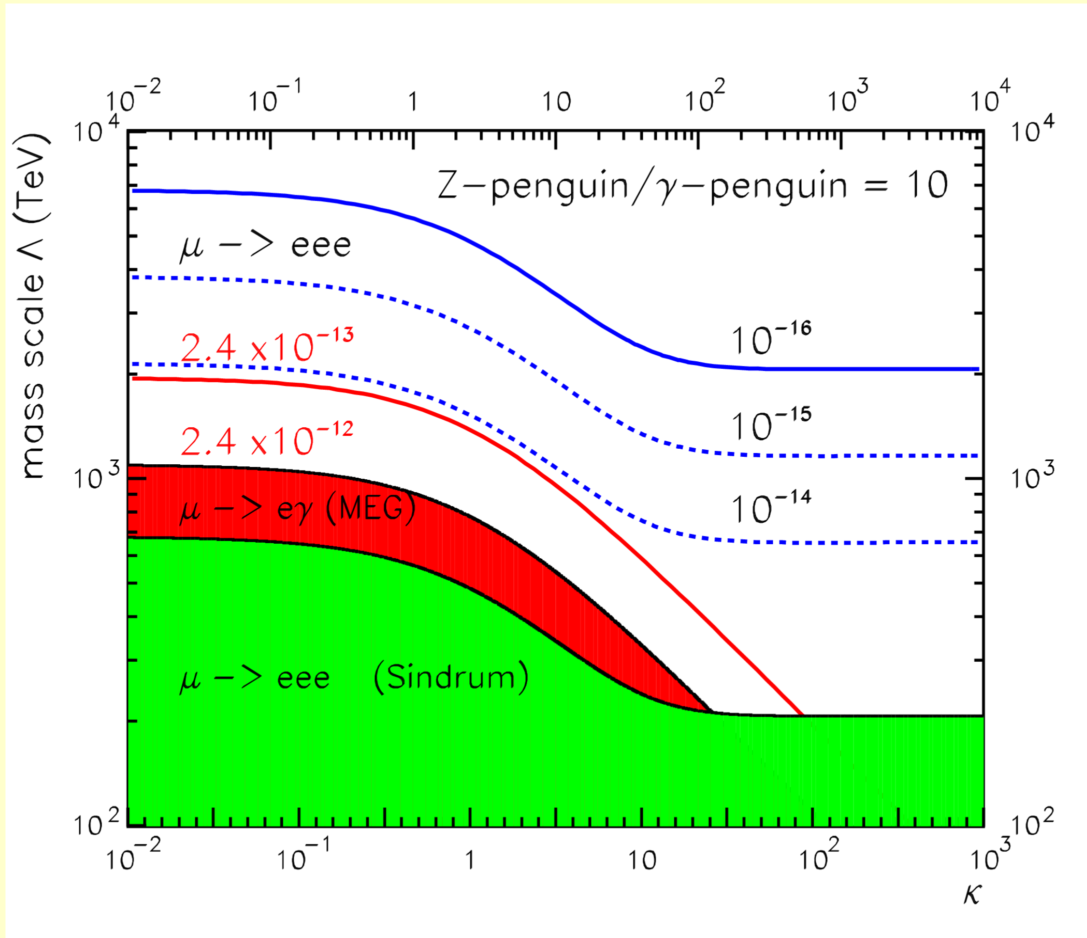
Model Independent Comparison

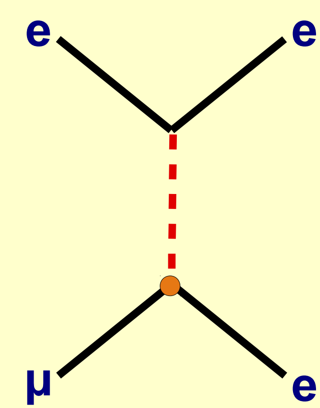
Z-penguin enhanced by factor 10





$\kappa = 0$





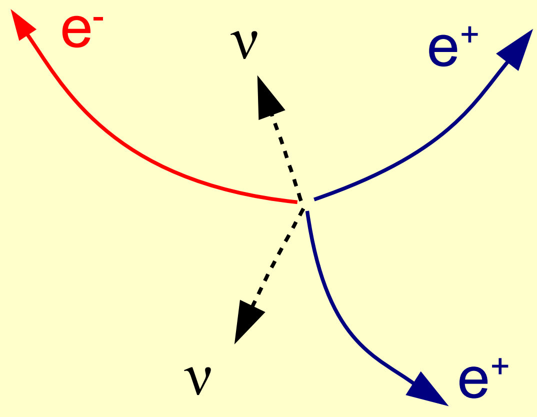
$\kappa = \infty$

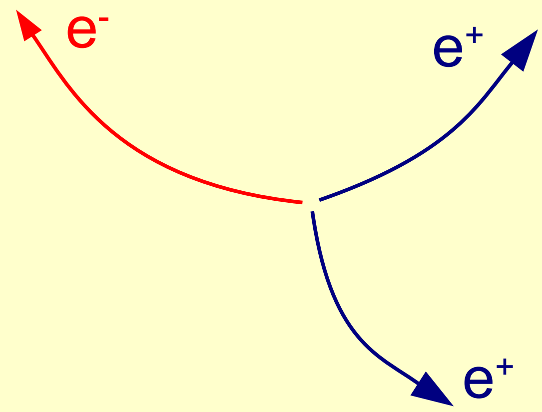
Improvement of existing SINDRUM limit by 2 orders of magnitude is relevant!

Experimental Situation

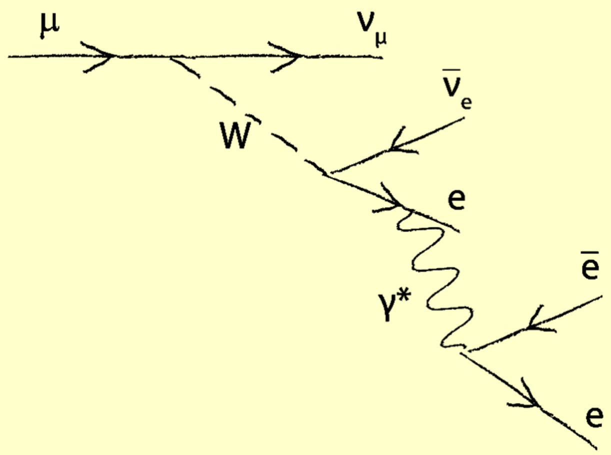
Backgrounds

Irreducible BG: radiative decay with internal conversion





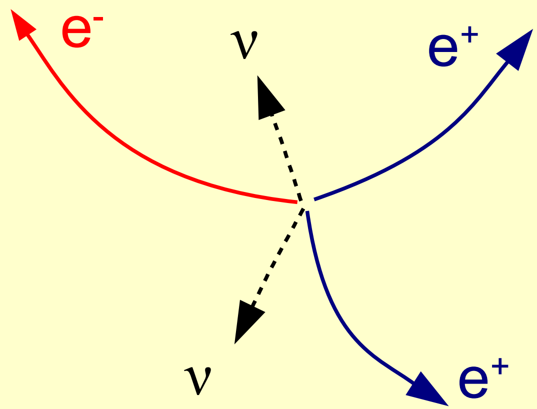
$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



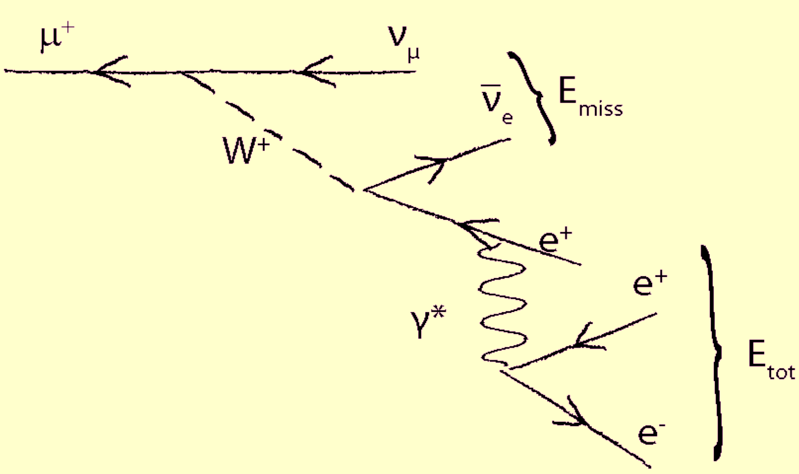
$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

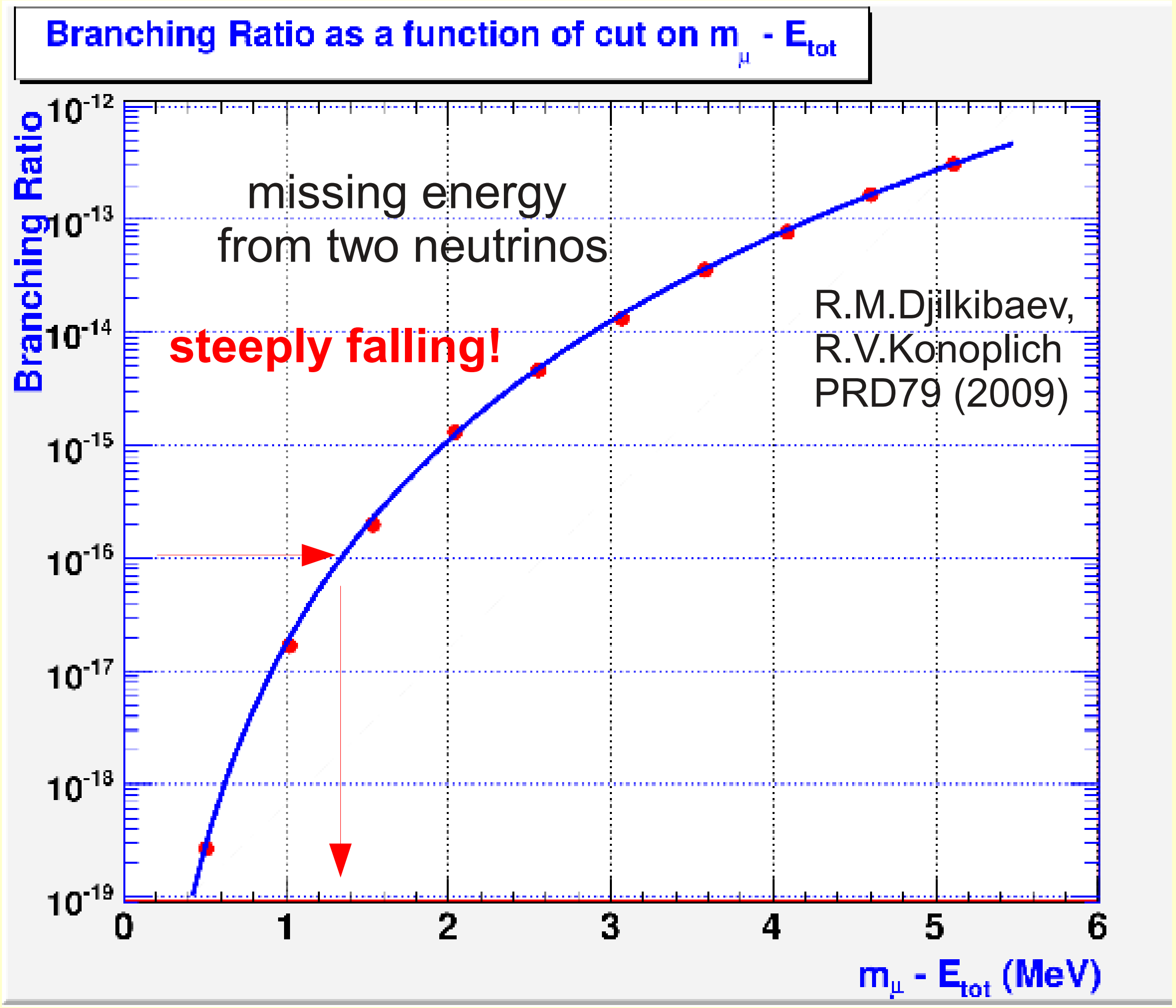
Backgrounds

Irreducible BG: radiative decay with internal conversion



B(μ⁺ → e⁺e⁺e⁻ νν) = 3.4 ·10⁻⁵





Backgrounds

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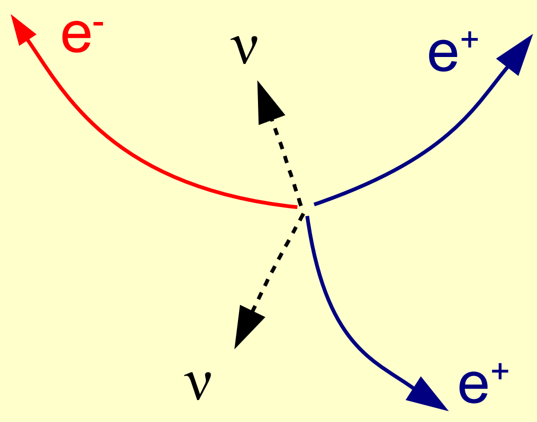
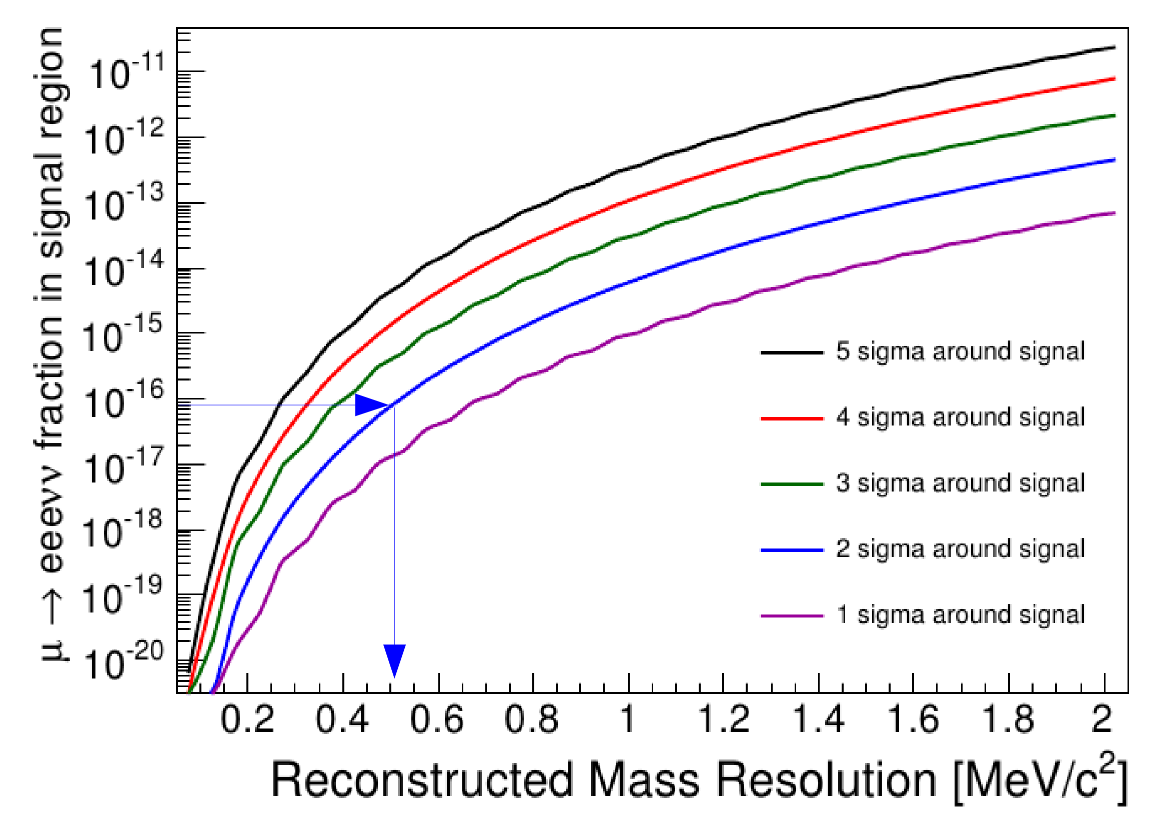
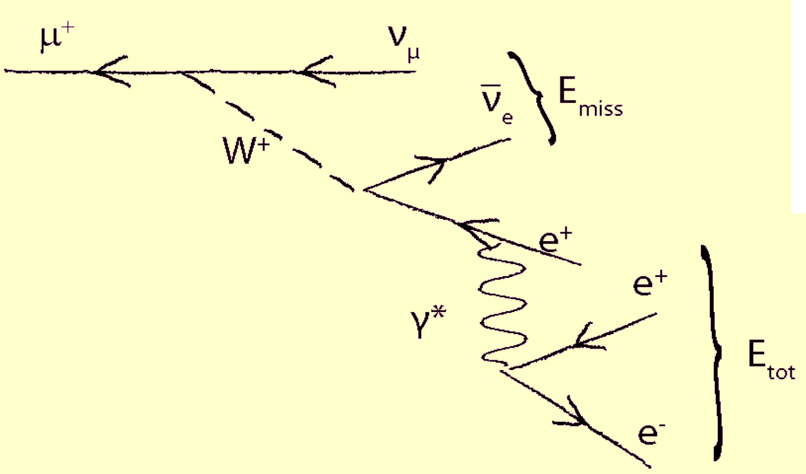




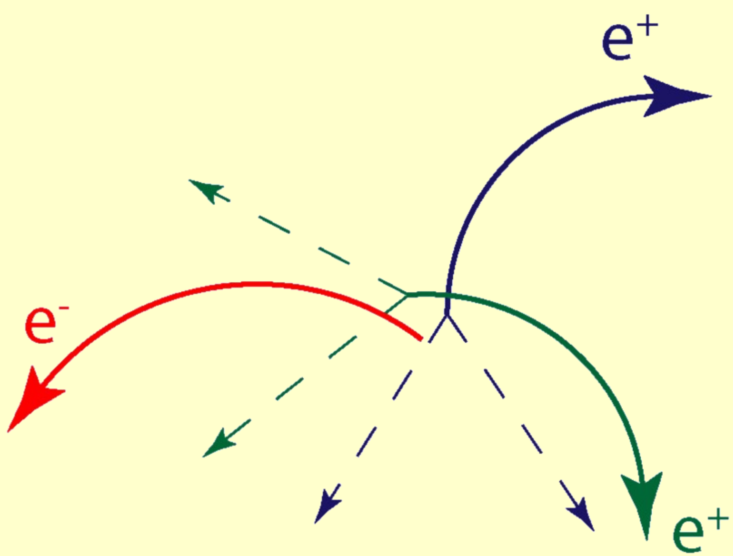
$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$

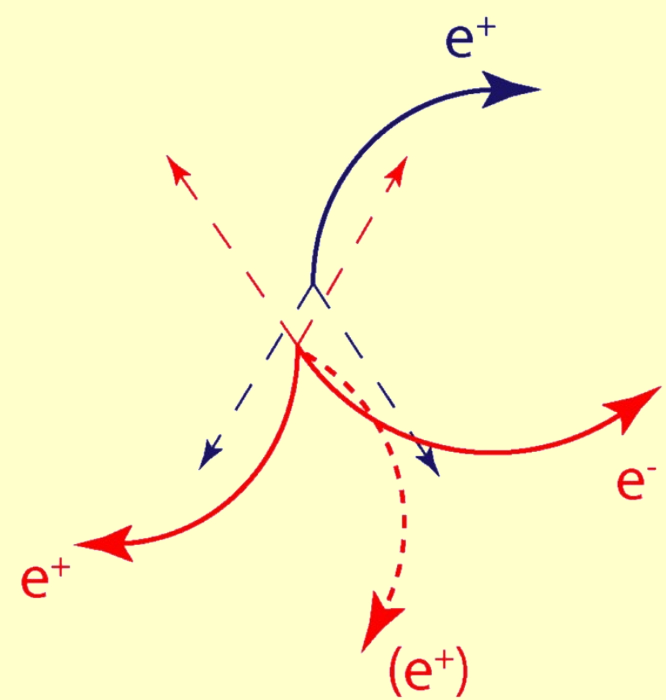


very good momentum +
total energy resolution required!

Accidental Backgrounds

- Overlays of two normal muon decays with a (fake) electron
- Electrons from: Bhabha scattering, photon conversion, mis-reconstruction



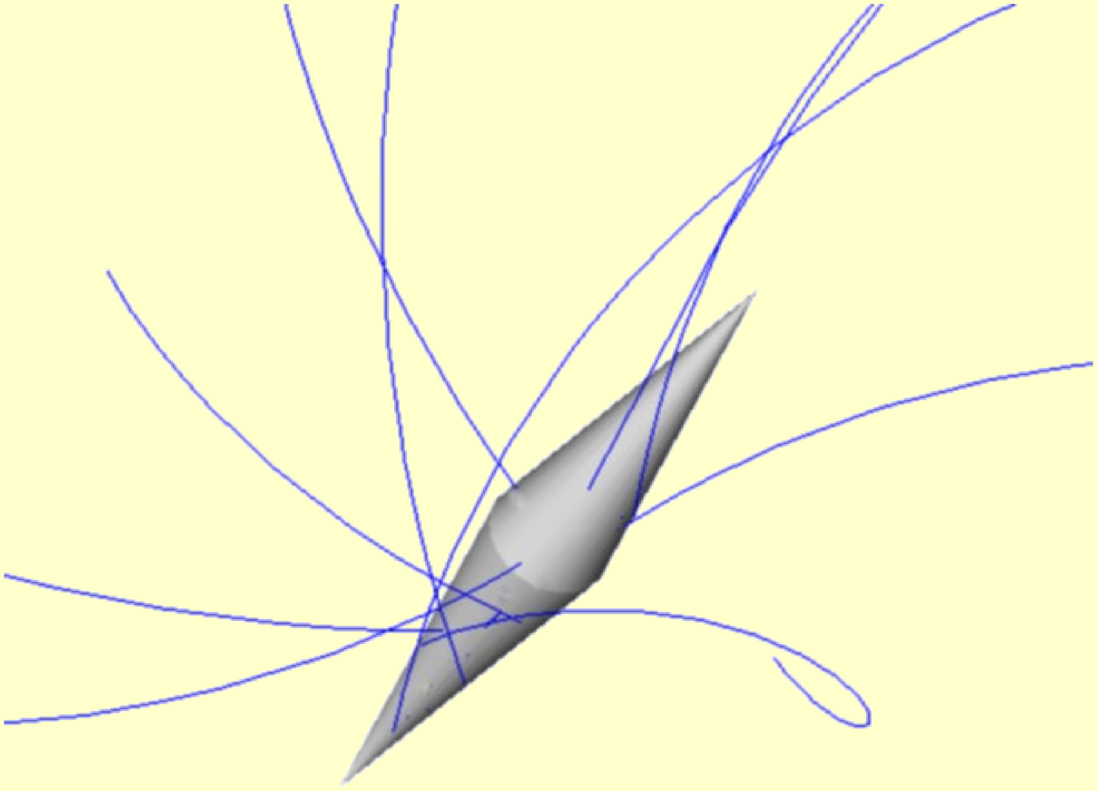


Need excellent:

- **vertex resolution**
- **timing resolution**
- **kinematic reconstruction**

The Target

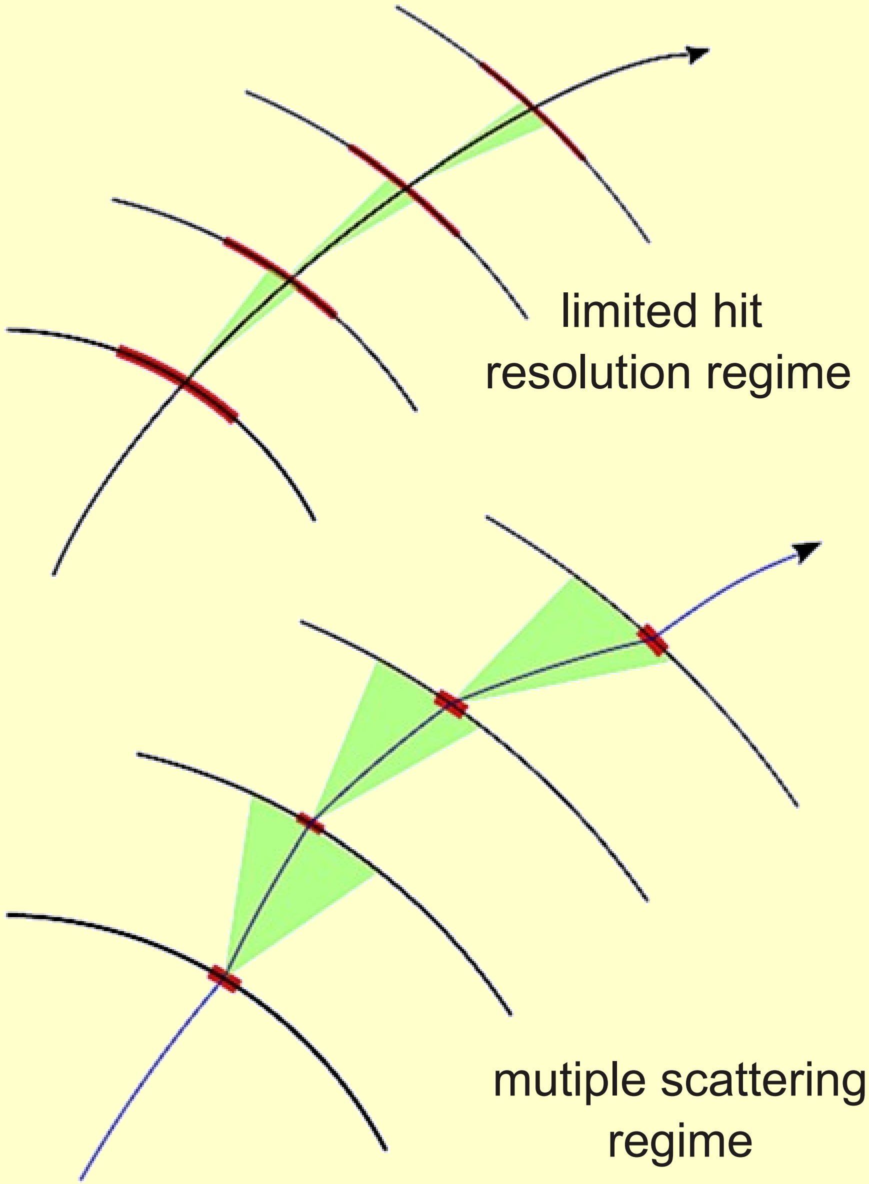
Spread muon decays in space and time



- DC Muon beam (PSI)
- about 4000 muons resting on target at same time
- large stopping target
- good **vertexing** and **timing** resolution required

e.g. Sindrum-like extended target
➔ hollow double cone (e.g. 30-80 μm Al)

Kinematic Resolution + Multiple Scattering



- Muon decay:

  → electrons in low momentum range
  $p < 53$ MeV/c

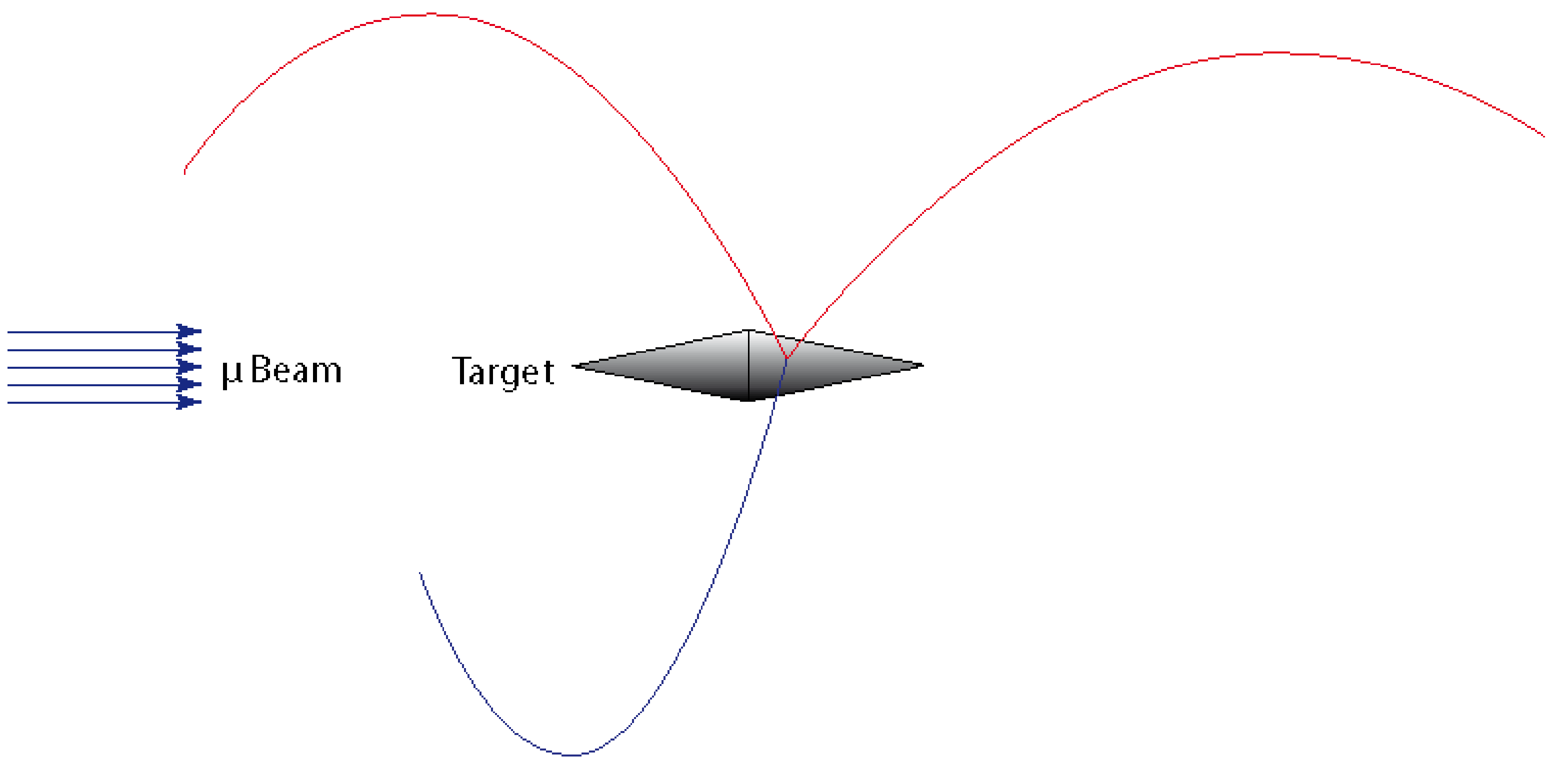
- Multiple scattering is dominant!
- **Need thin, fast and high resolution detectors (tracking + time of flight)**

$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X / X_0}$$

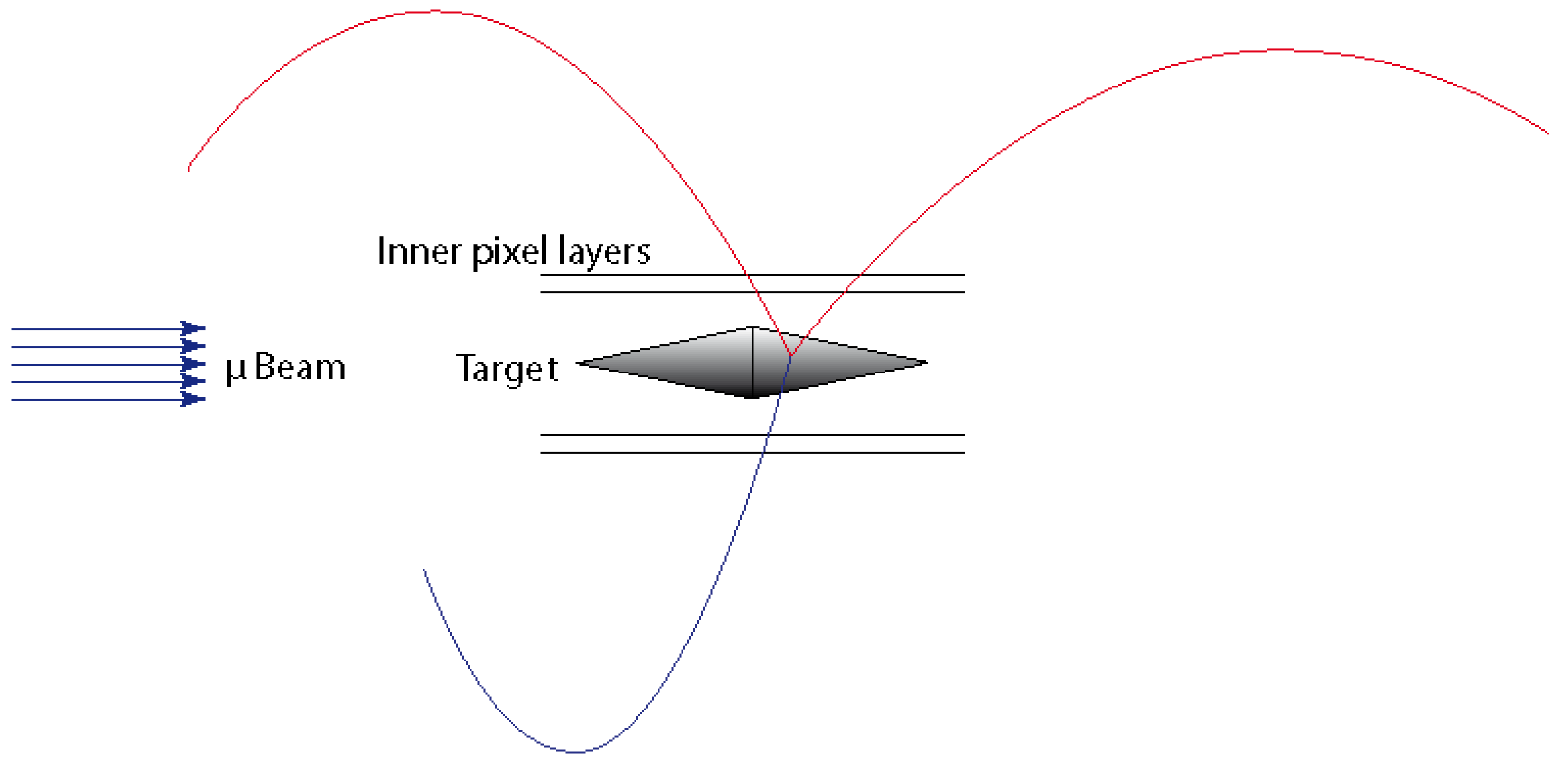
Experimental Proposal

Mu3e Baseline Design

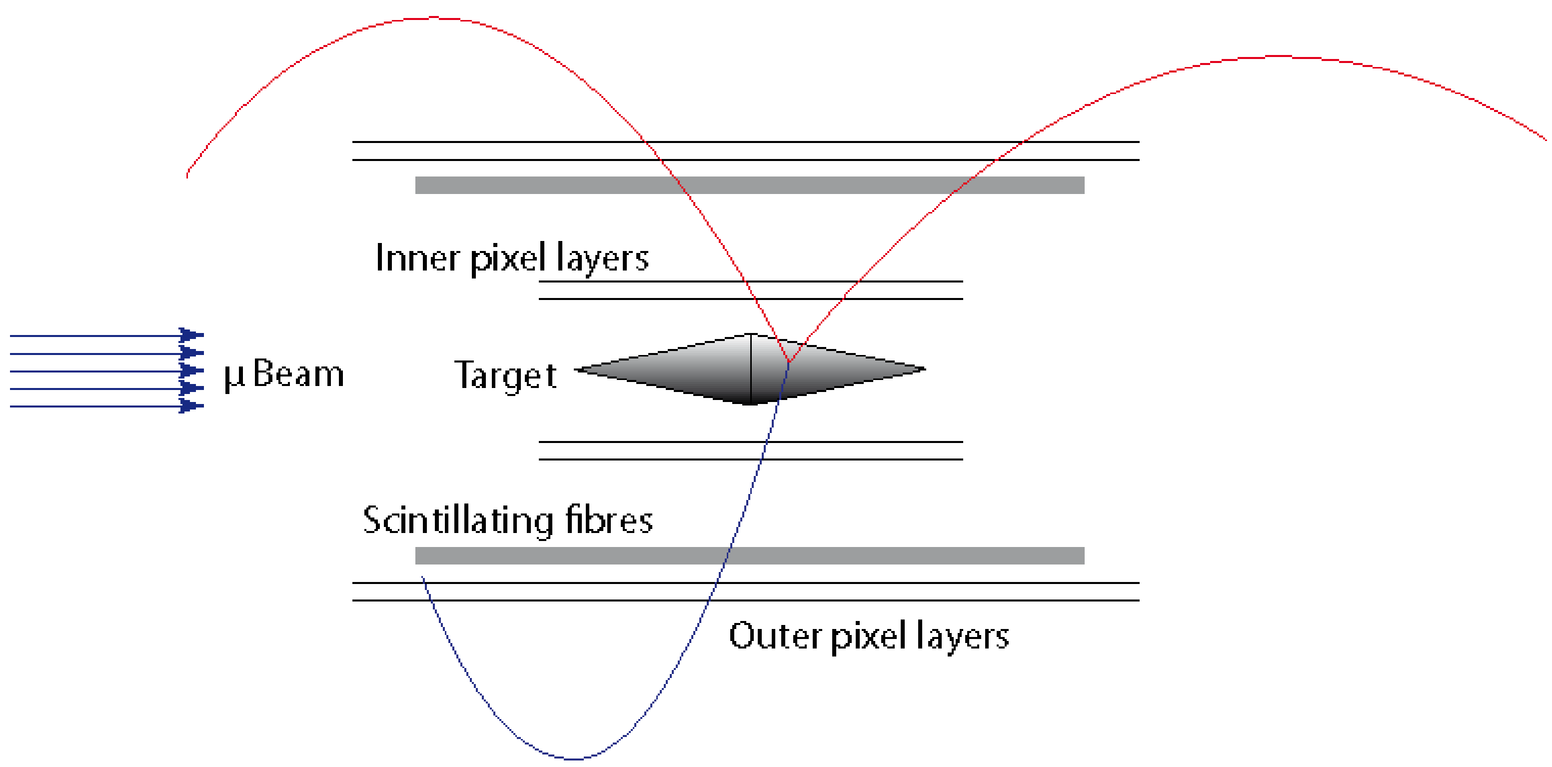
Mu3e Baseline Design



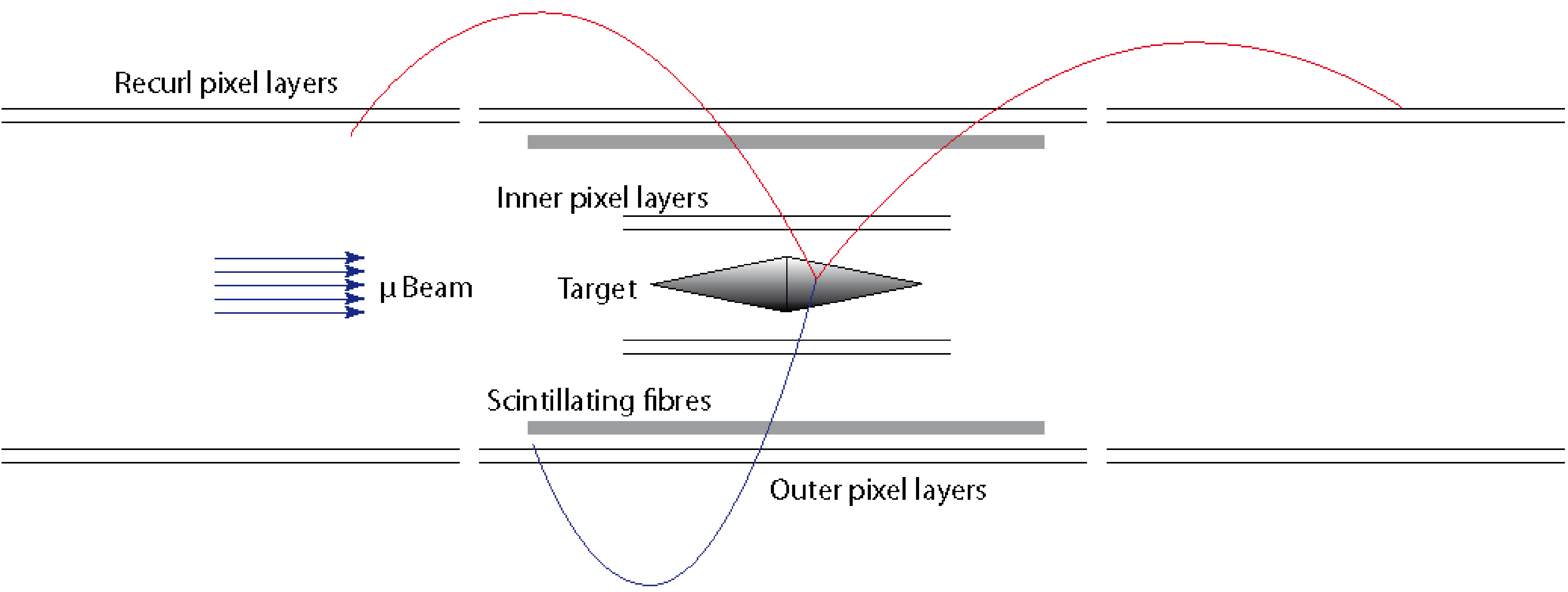
Mu3e Baseline Design



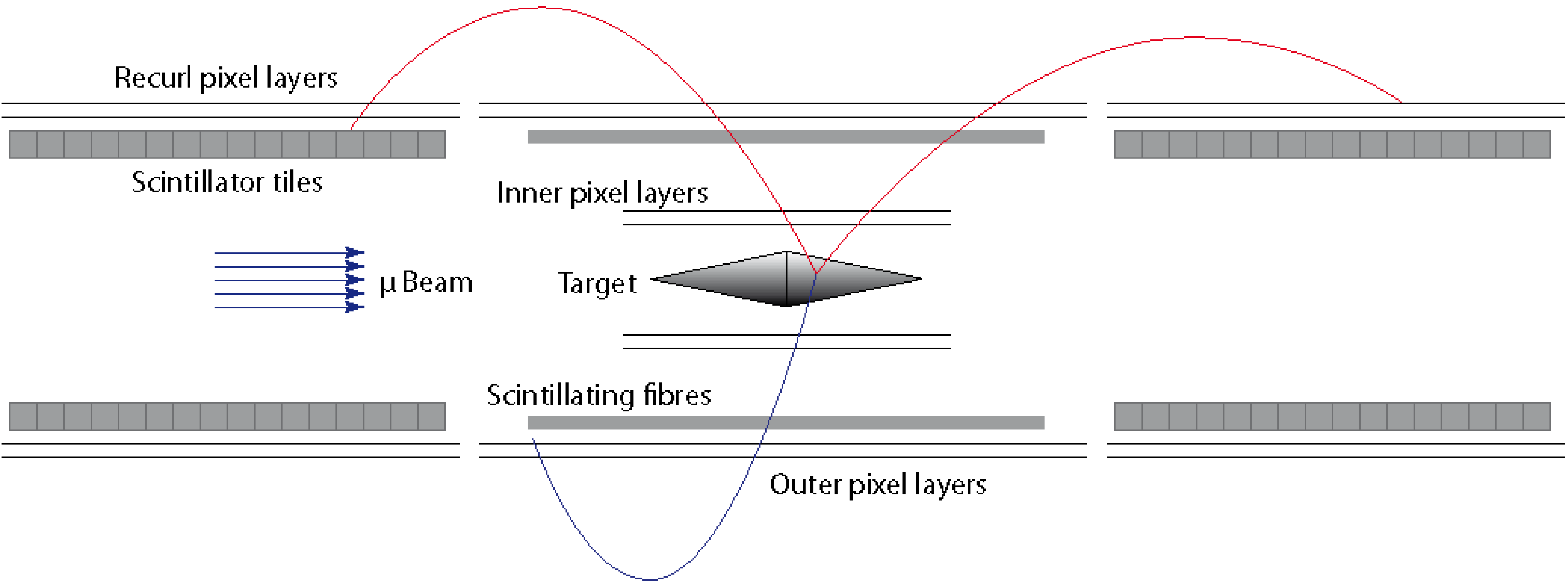
Mu3e Baseline Design



Mu3e Baseline Design



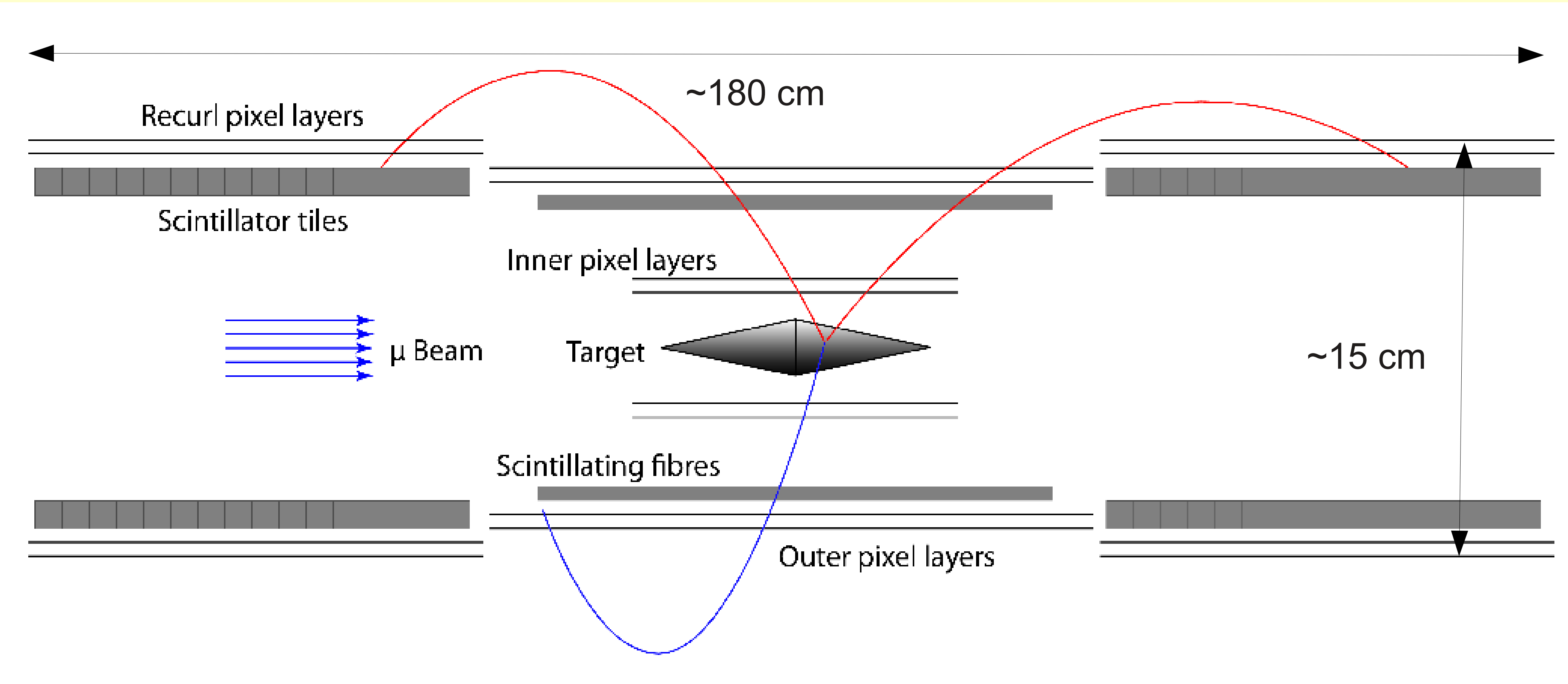
Mu3e Baseline Design



Mu3e Baseline Design

Long cylinder!

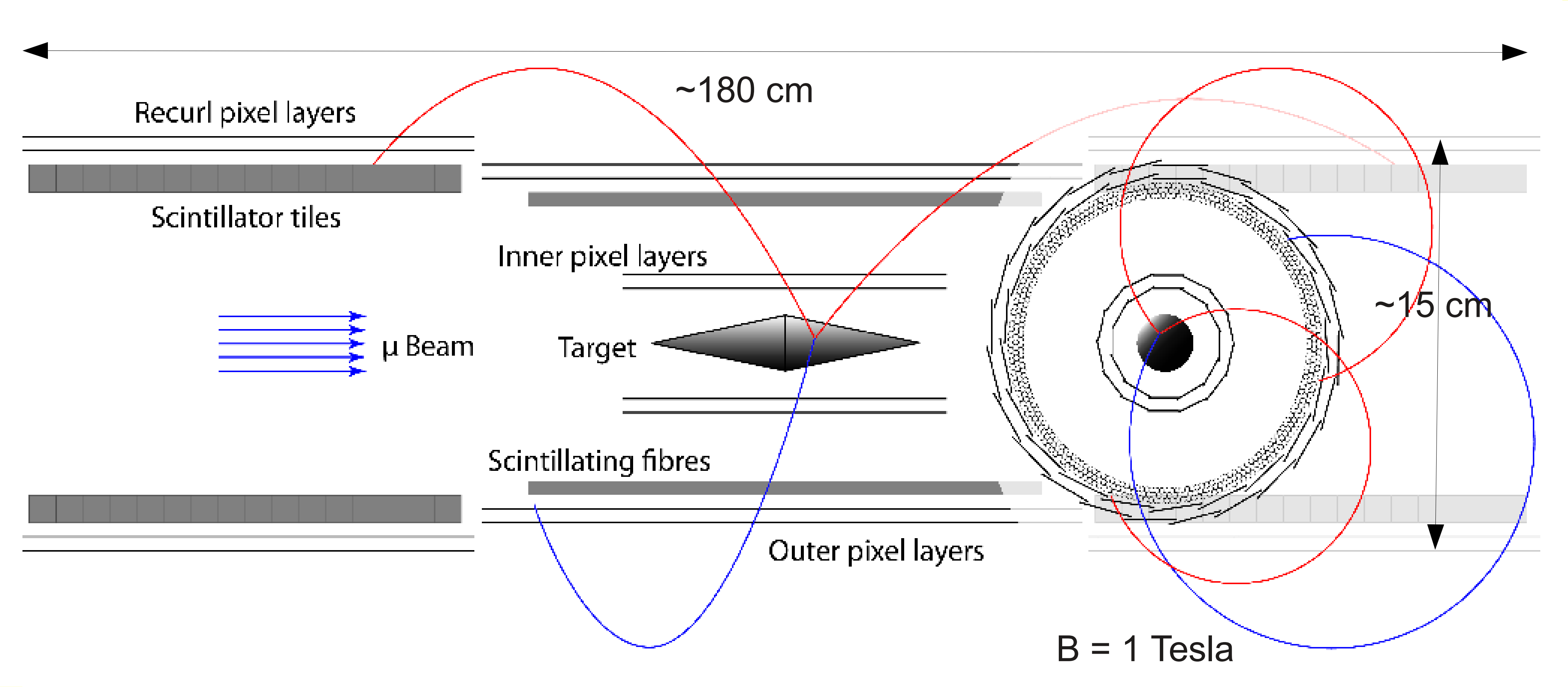
not to scale!



Mu3e Baseline Design

Long cylinder!

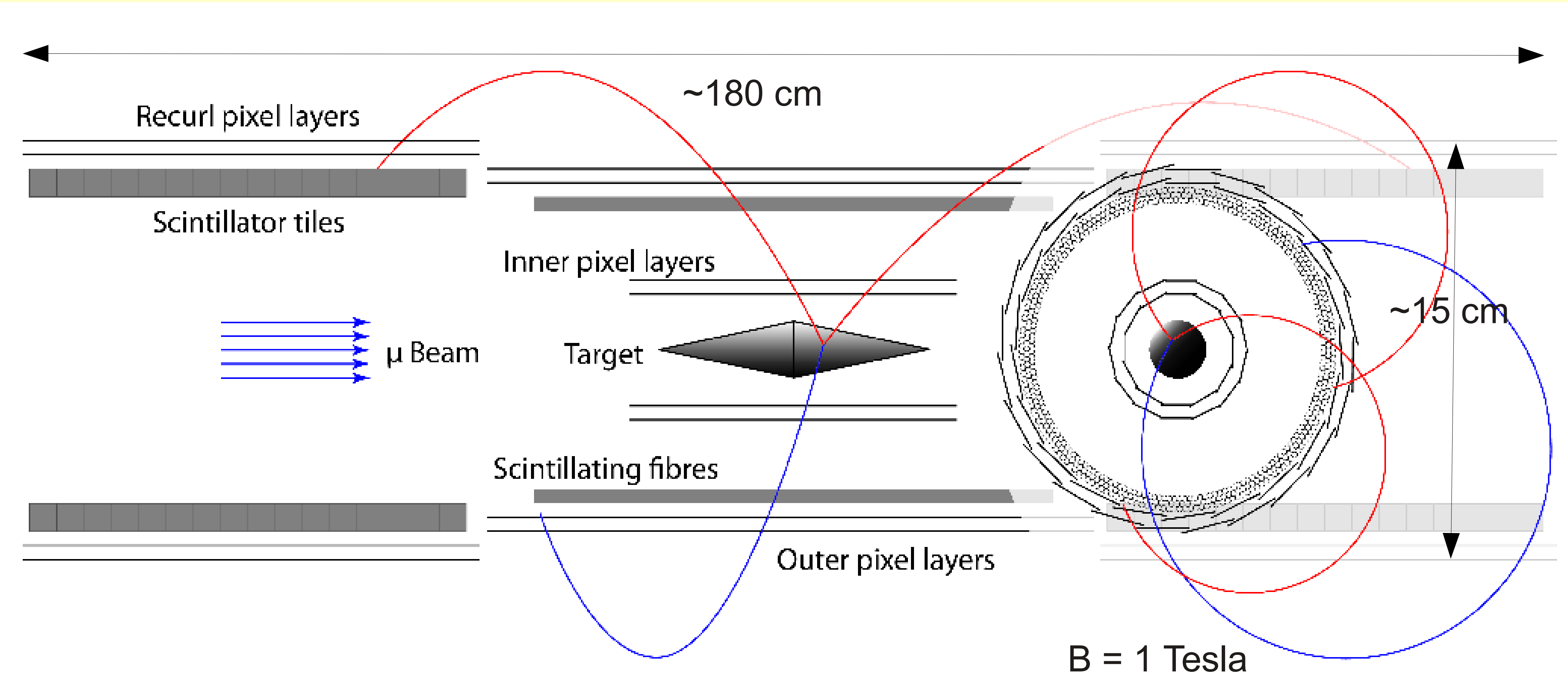
not to scale



Mu3e Baseline Design

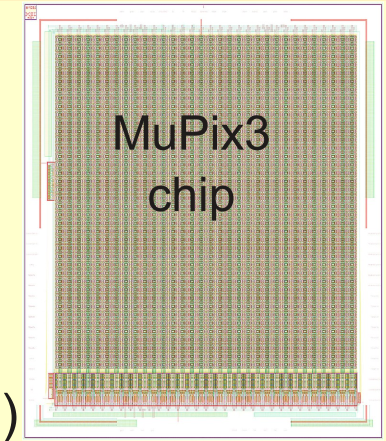
Long cylinder!

not to scale

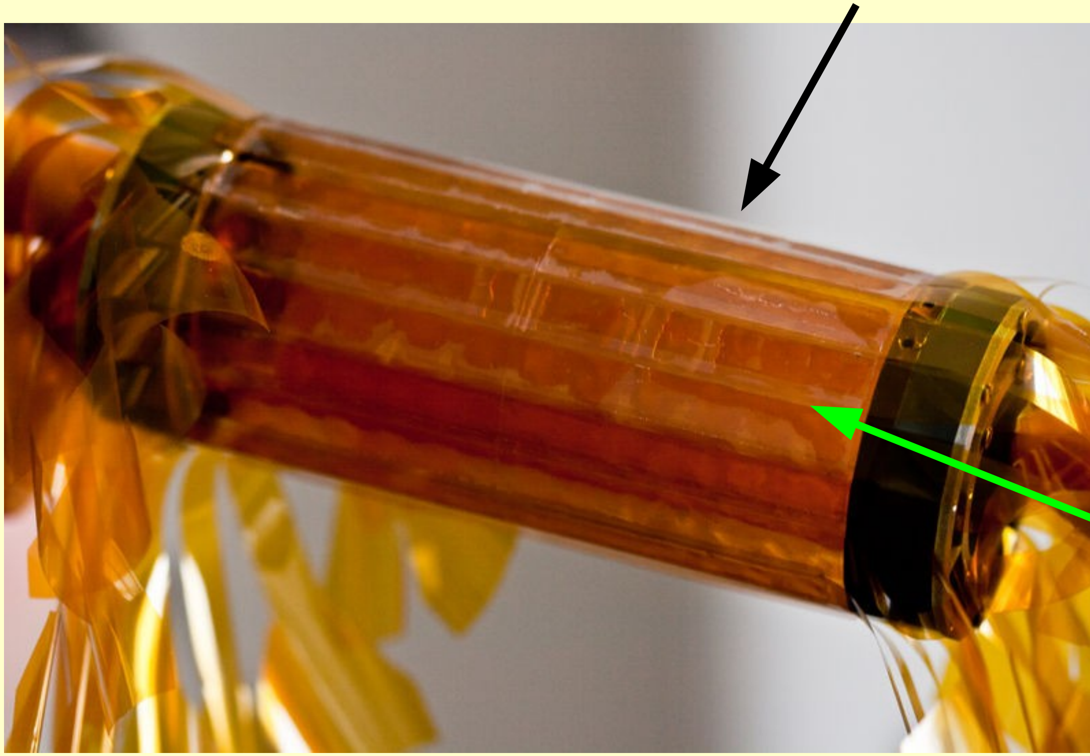


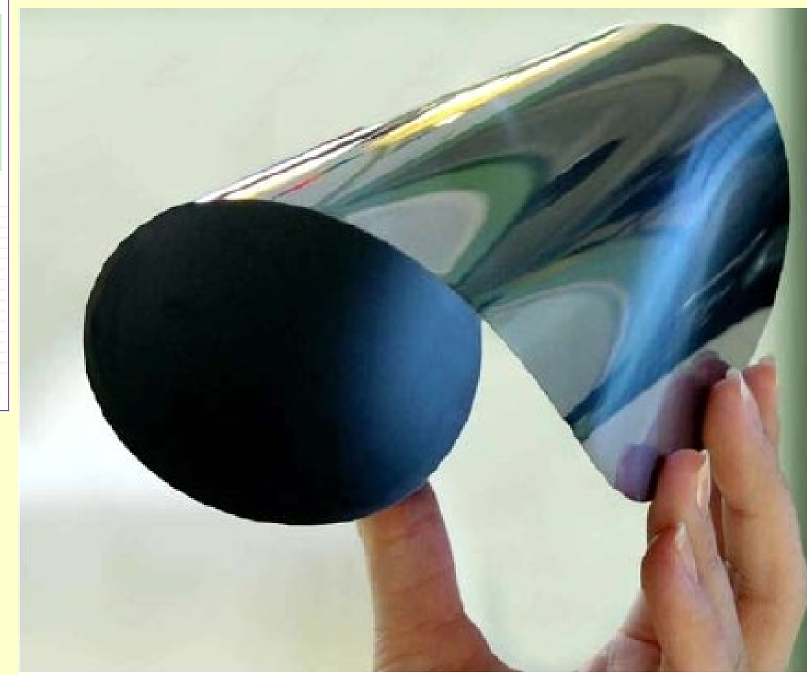
Geometrical acceptance **~70 %** for **$\mu^+ \rightarrow e^+e^+e^-$** decay

Mechanical Prototypes

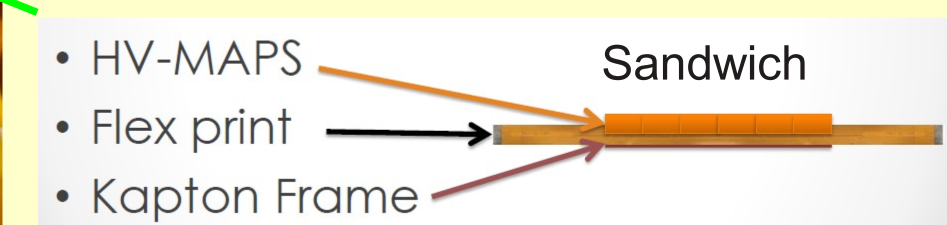


Ultra-thin detector mock-up:
sandwich of 25 µm Kapton®
and 50/100 µm glass (instead of Si)

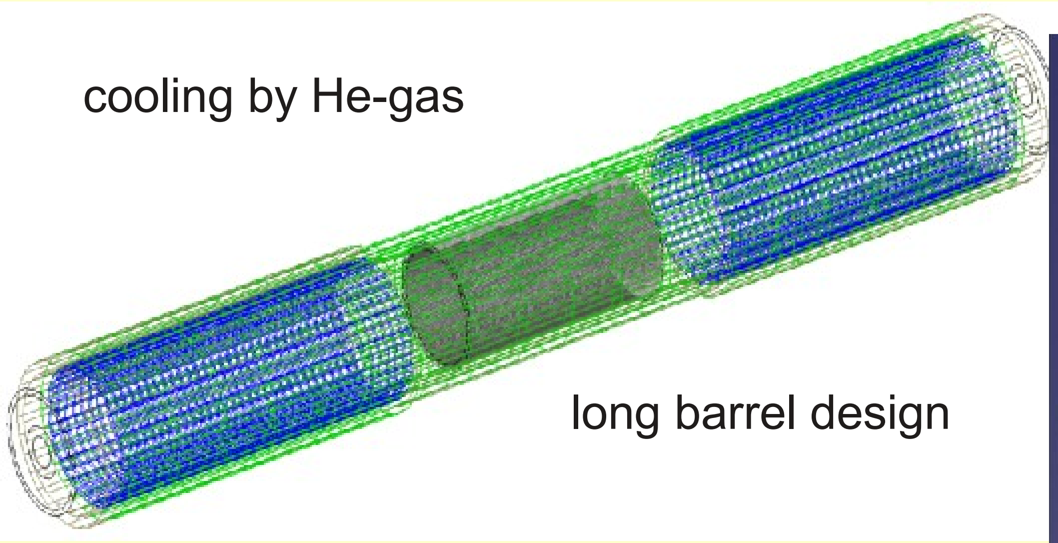


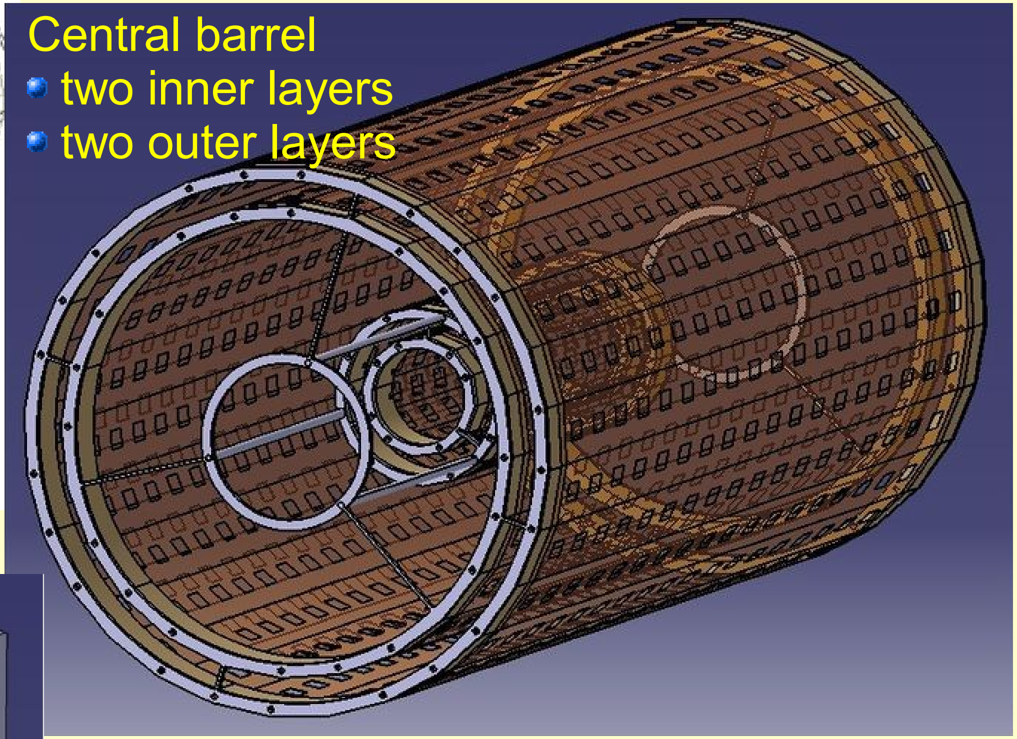


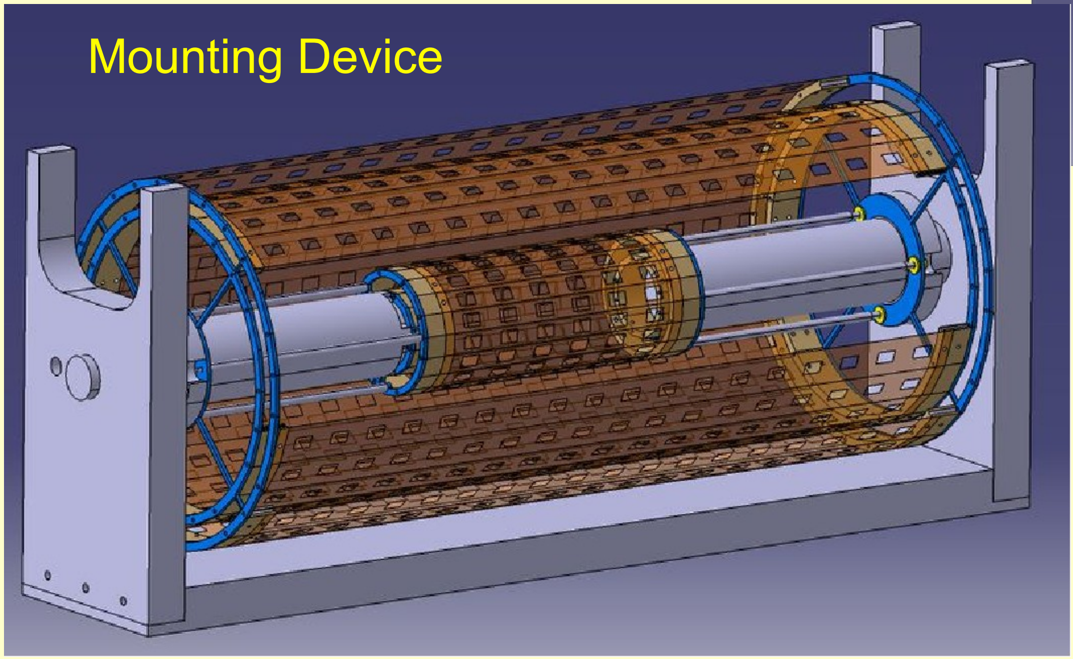
50 mu silicon wafer



Silicon Pixel Detector



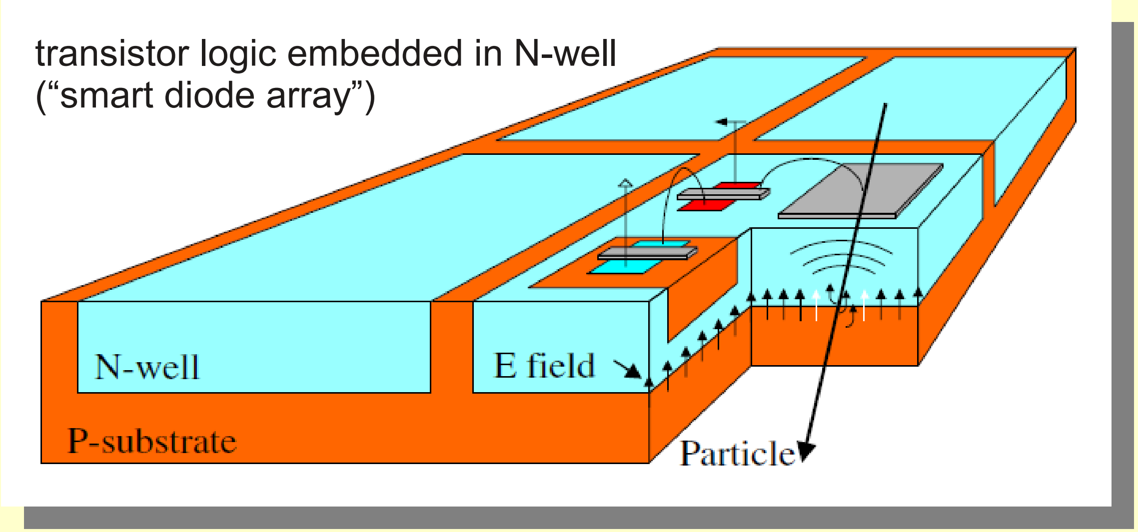




Component	thickness [μm]	X/X_0 [%]
Kapton frame	25	0.018
Kapton flex-print	25	0.018
Aluminum traces (50 % coverage)	15/2	0.008
HV-MAPS	50	0.053
Adhesive	10	0.003
Full detector layer	125	0.100

Silicon Pixel Detector

I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg)



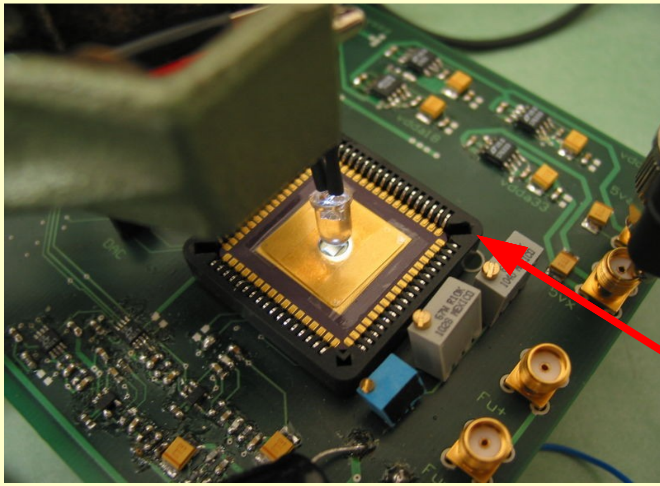
Technology Choice

High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

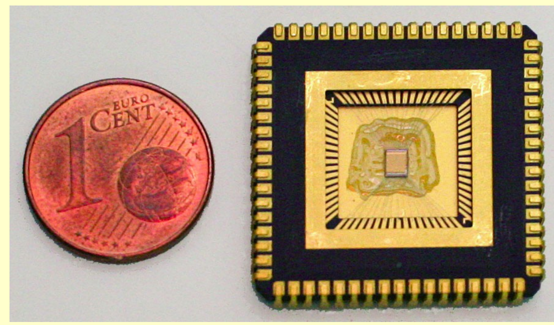
- high precision → pixels 80 x 80 μm^2
- can be "thinned" down to ~**30 µm** (~ 0.0004 X_0)
- low production costs (standard HV-CMOS process, 60-80 V)
- active sensors → small RO bandwidth, no bump bonding required
- triggerless and fast readout (LVDS link integrated)
- low power

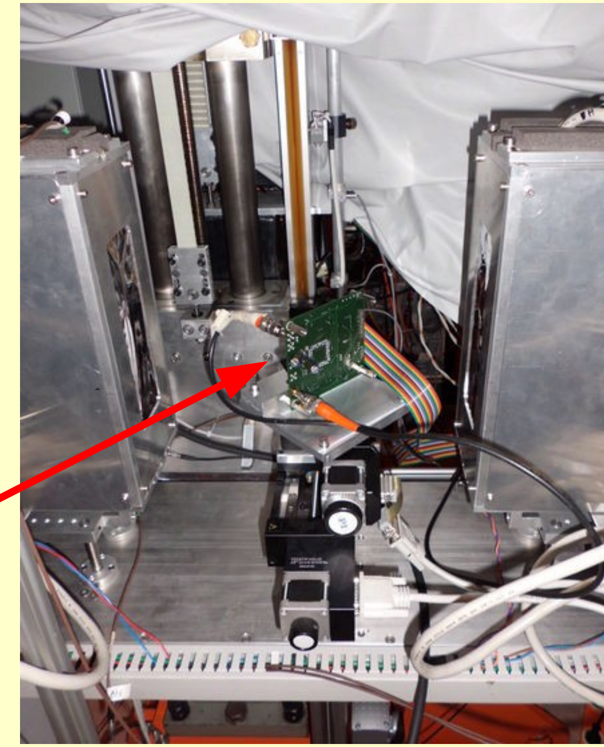
Pixel Detector Tests

MuPix2 characterization in lab

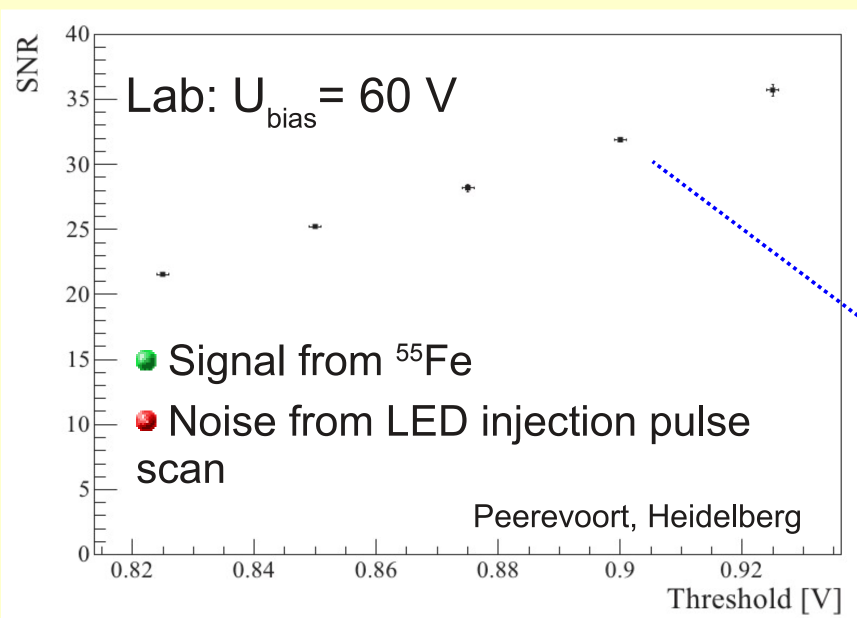


MuPix2 at CERN beam test





prototype 180 nm
(MuPix2)



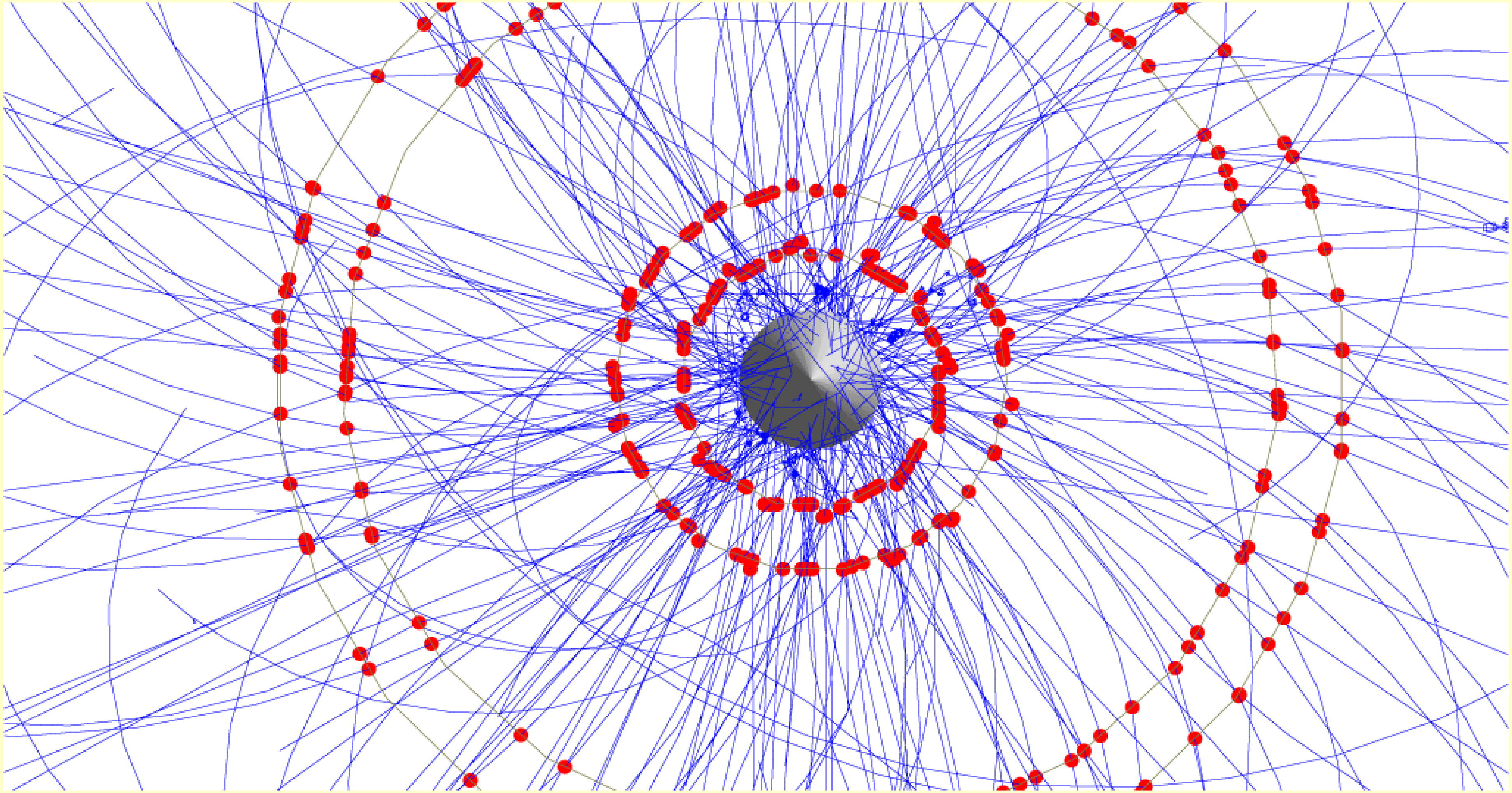
<u>CERN Test Beam:</u>

- 180 GeV pions
- low bias voltage V_{bias}=56 V
- threshold V_{th}=0.9 V
- ~95% single hit efficiency (preliminary)

Timing

Pixel Detector: Readout Frames @ 20 MHz

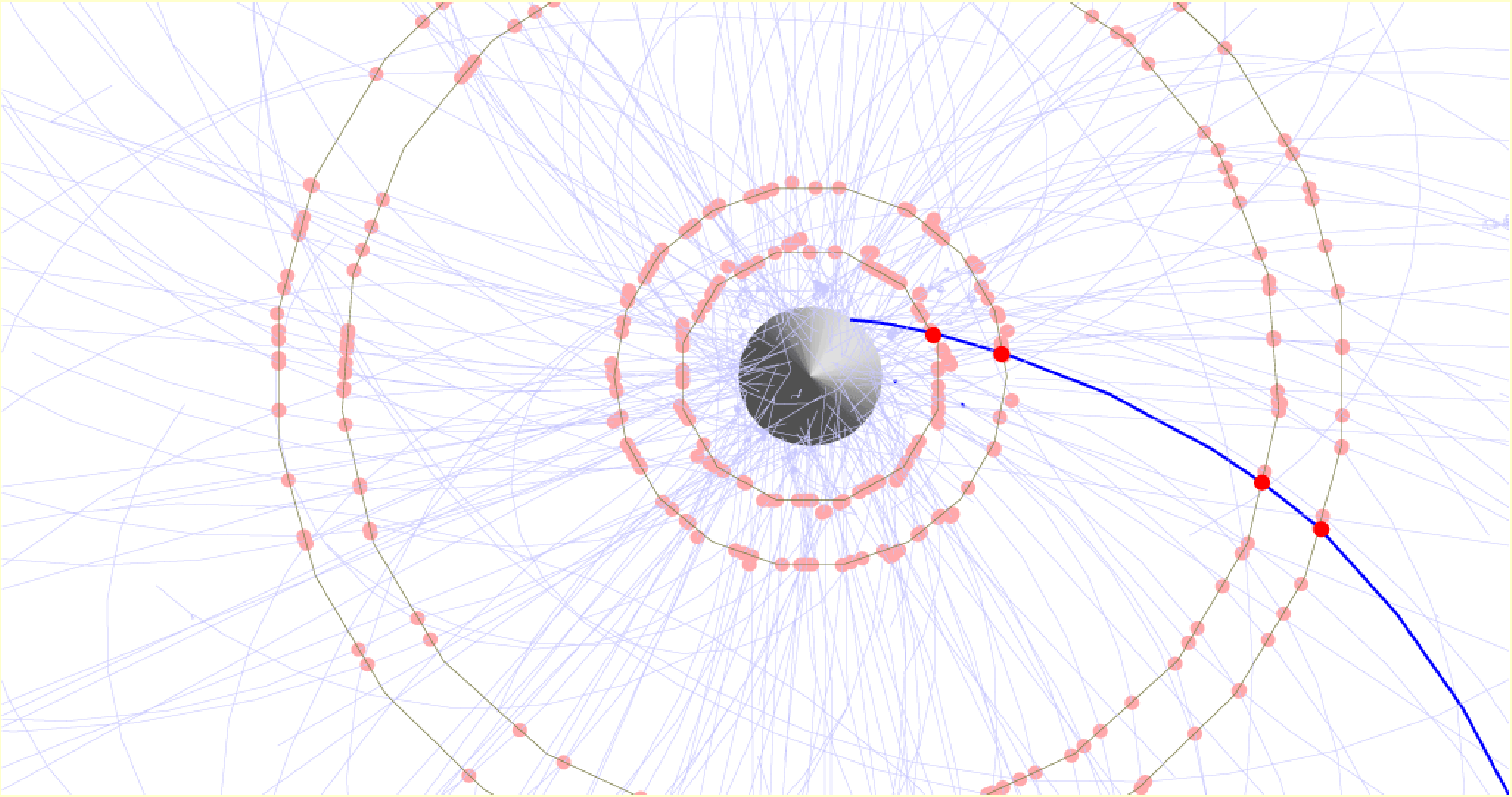
100 muon decays @ rate $2 \cdot 10^9$ muon stops/s



50 ns snapshot

Pixel: Readout Frames 50 ns

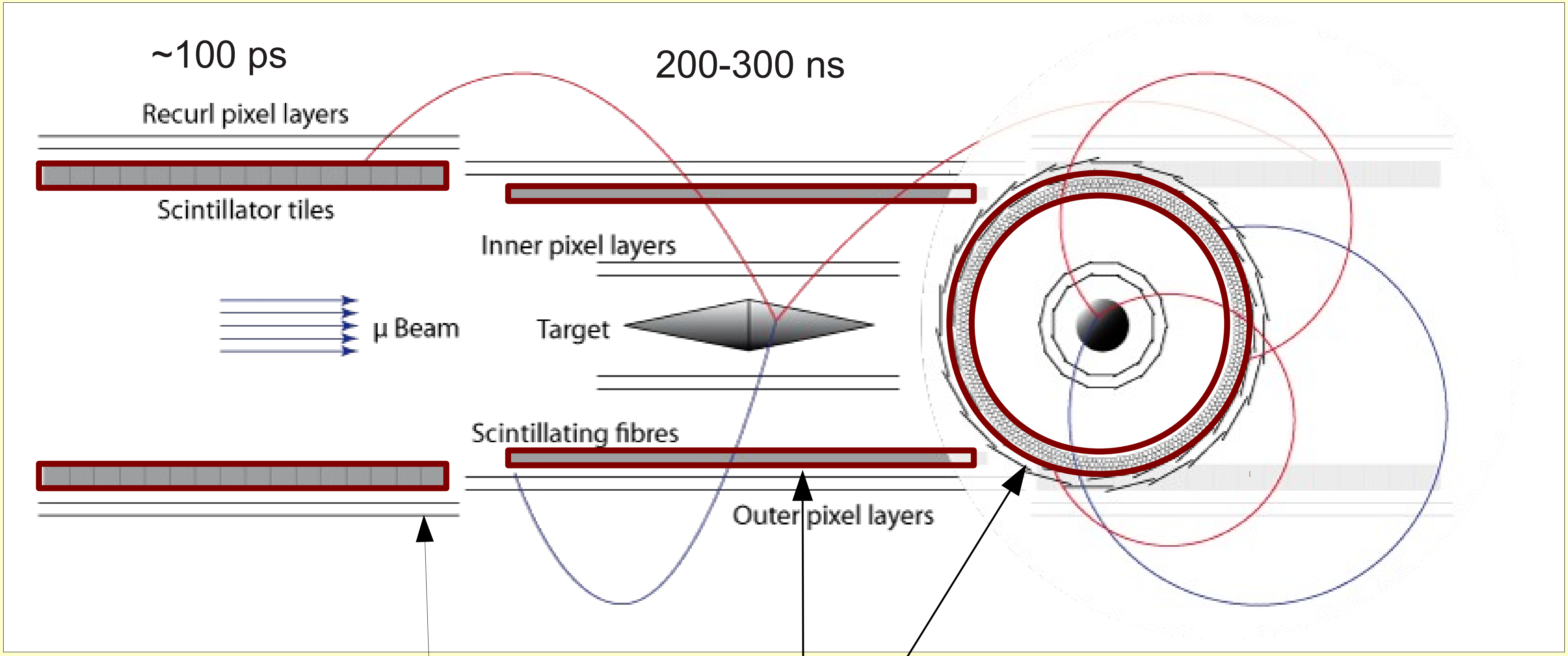
100 muon decays @ rate $2 \cdot 10^9$ muon stops/s



- **Additional Time of Flight (ToF) detectors required < 1ns**

Mu3e Baseline Design

not to scale

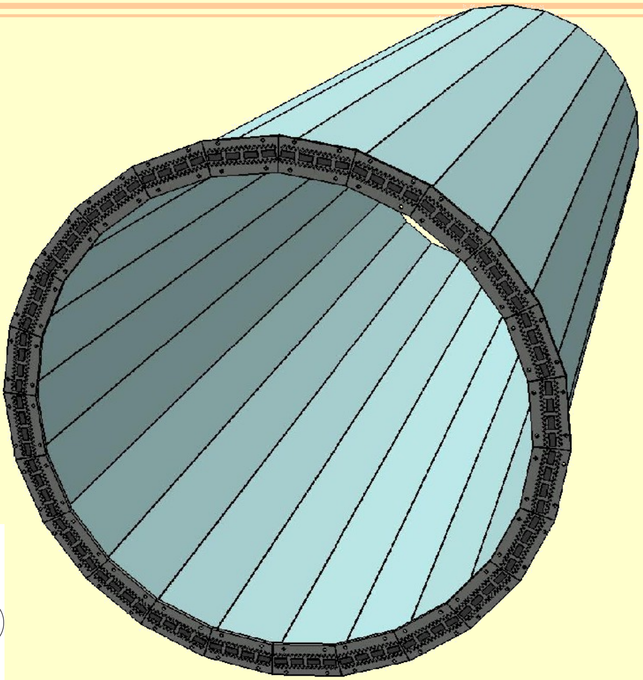


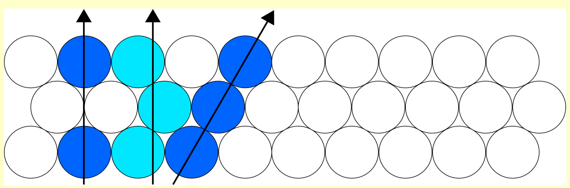
Scintillating tiles

Scintillating fibers

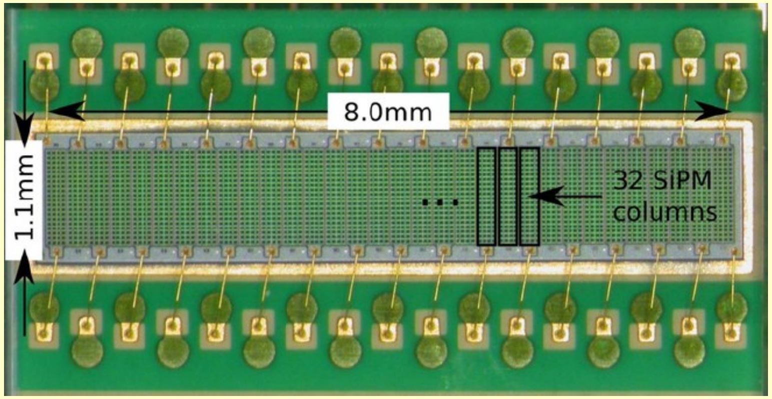
Scintillating Fiber Tracker

- high spatial resolution (matching with silicon hits)
- scintillating fibers Ø = 250 µm fibers (3 layers)
- photosensor
  - Hamamatsu MPPC arrrays (SiPM)
  - high gain >10^5, high frequency > 1MHz
  - alternative SiPM?
- time resolution <1 ns
- optical cross talk?
- prototypes in preparation

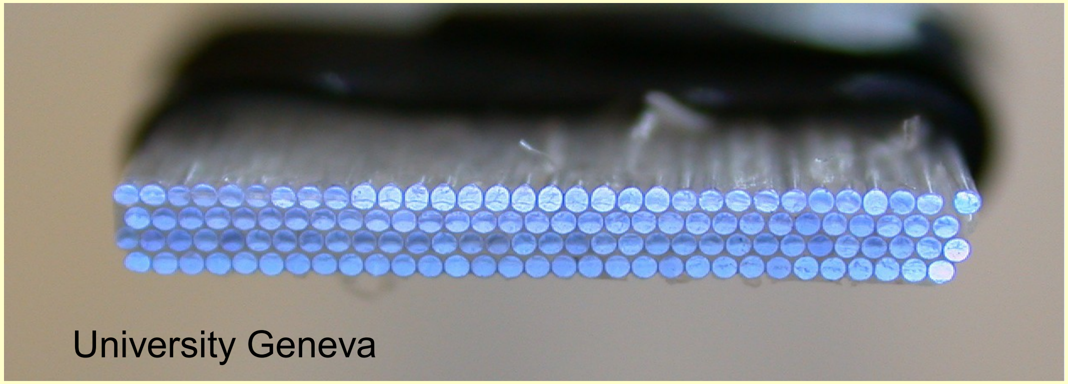




SiPm Array Hamamatsu MPPC 5883

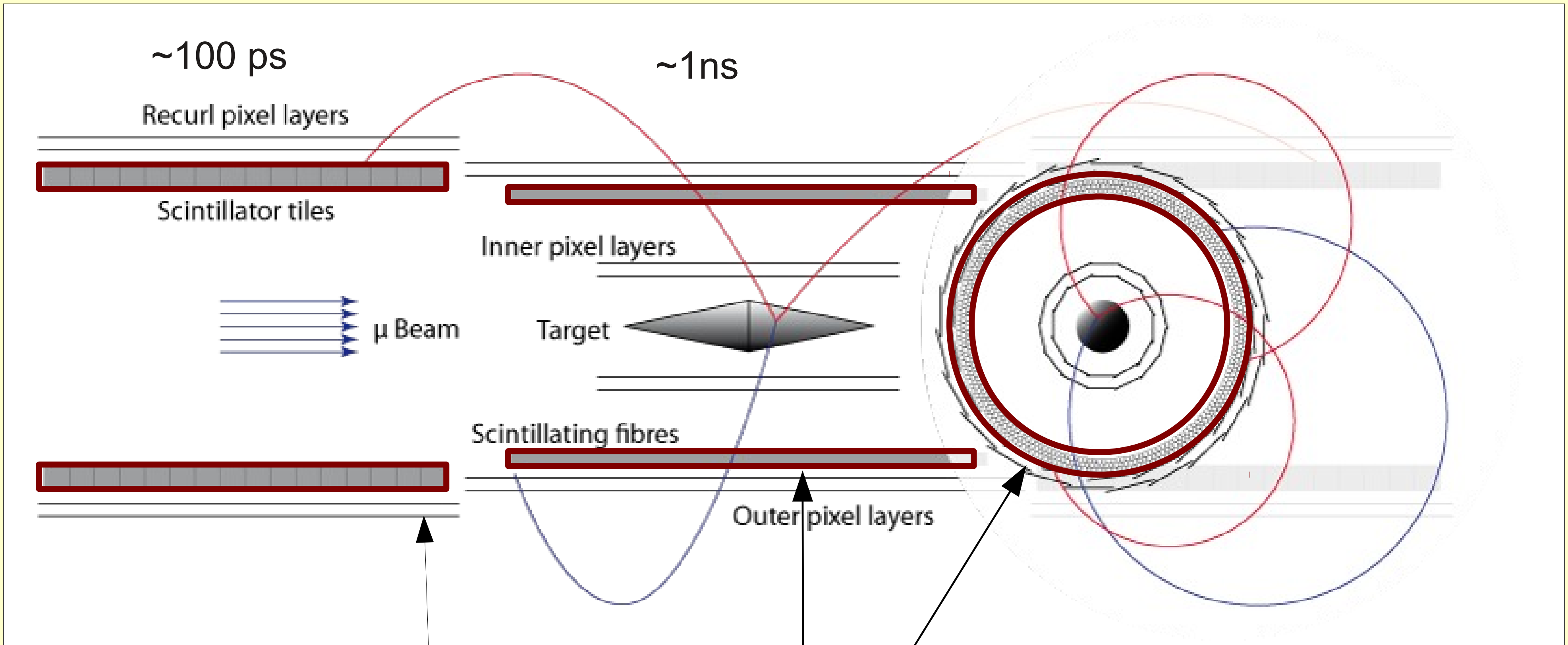


in collaboration with EPFL (Nakada et al.)



Mu3e Baseline Design

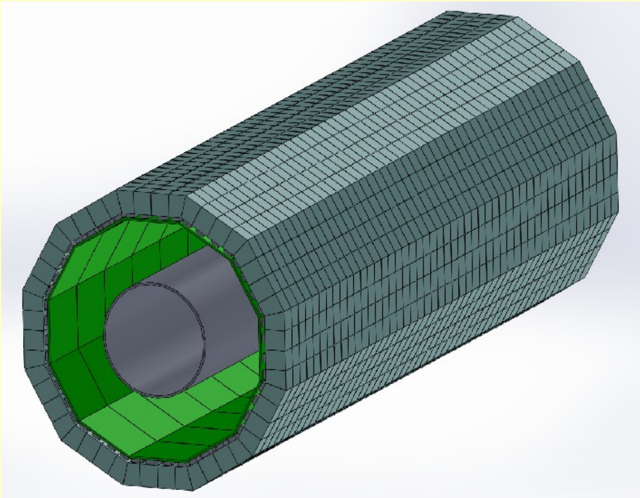
not to scale



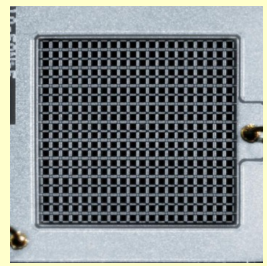
Scintillating tiles

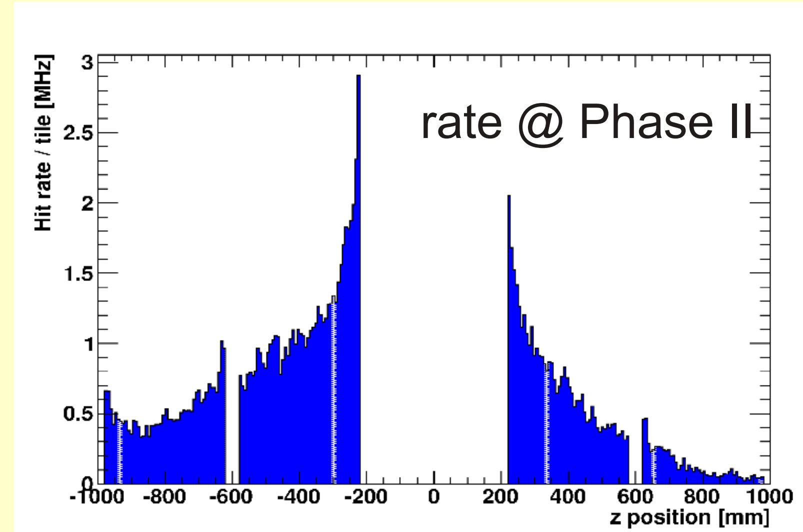
Scintillating fibers

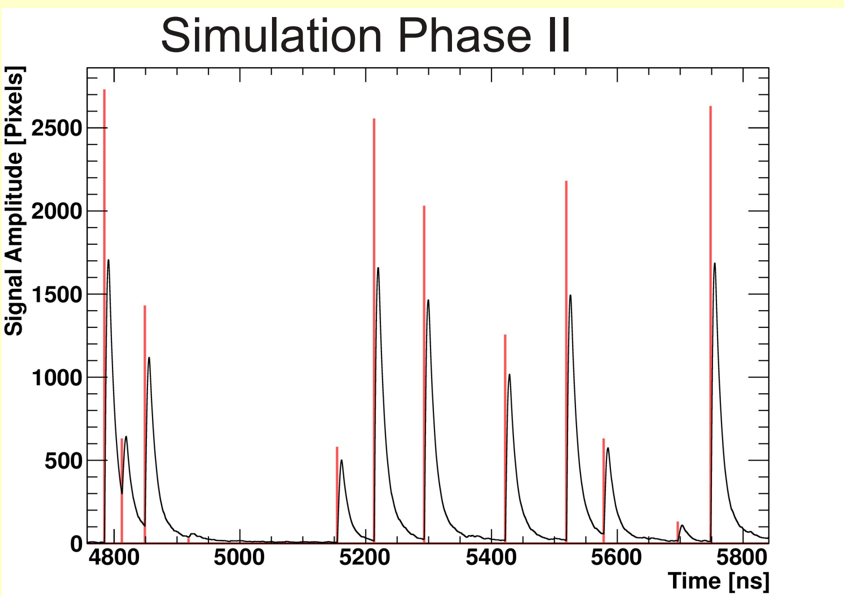
Scintillating Tile Detector

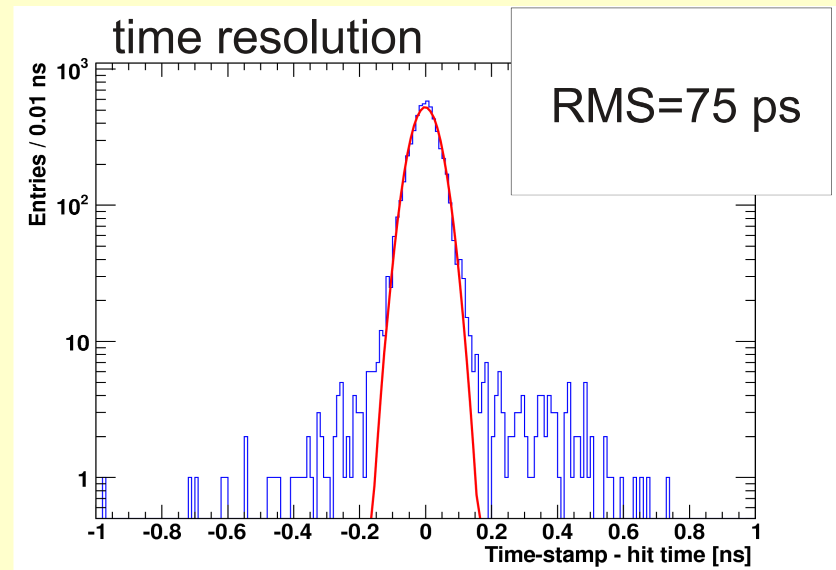


- scintillating tiles of size ~ 1 cm^2
- timing resolution of about 100 ps
- photosensors (SiPM)









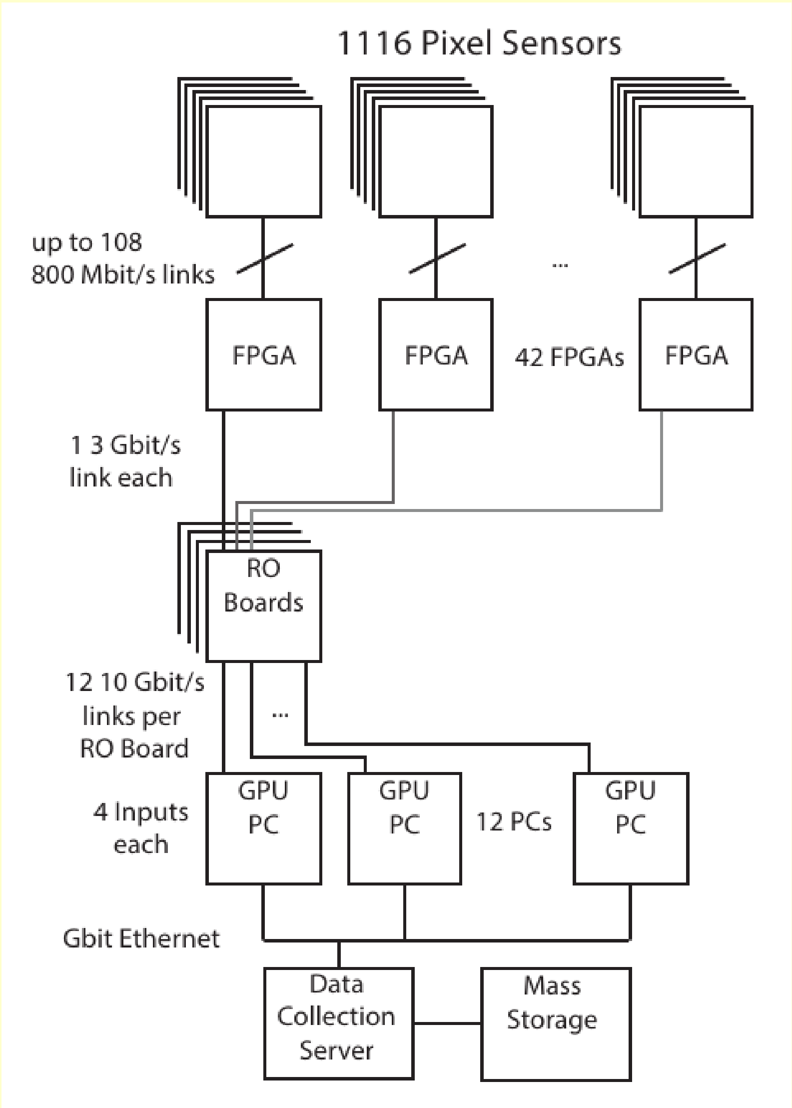
Timing information helps to reduce accidental backgrounds

Data Acquisition

Central pixel detectors (Phase I)
- frontend data rate of 90 Gbit/s

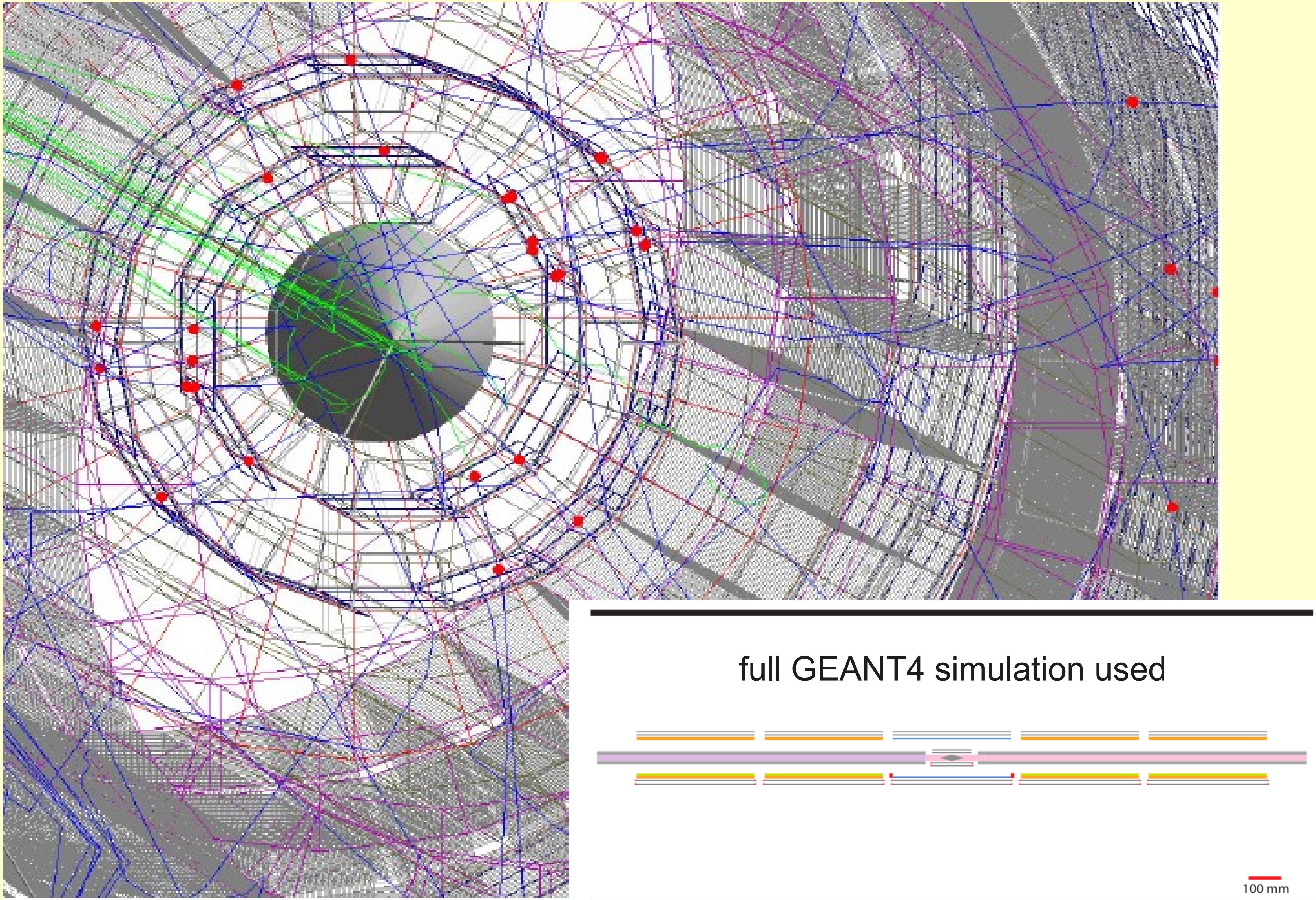
Full pixel detector (Phase II)
- frontend data rate of 1500 Gbit/s

Online event reconstruction using
- Graphics Processing Units (GPUs)



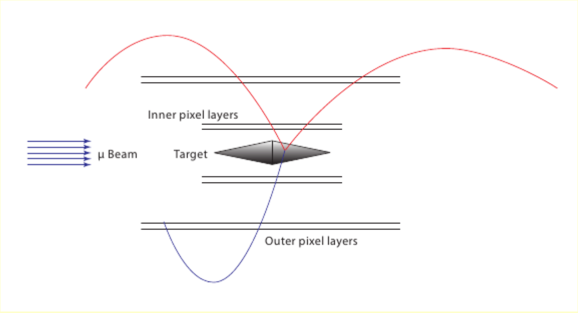
Logging rate ~50-100 MB/s

Simulation



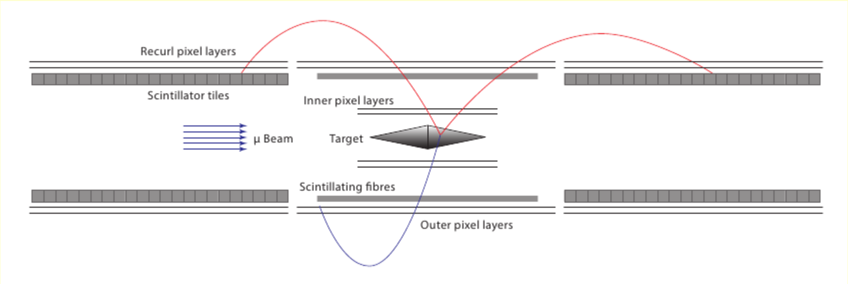
Reconstruction

Phase IA:
rate ≤ 10^7 muons/s



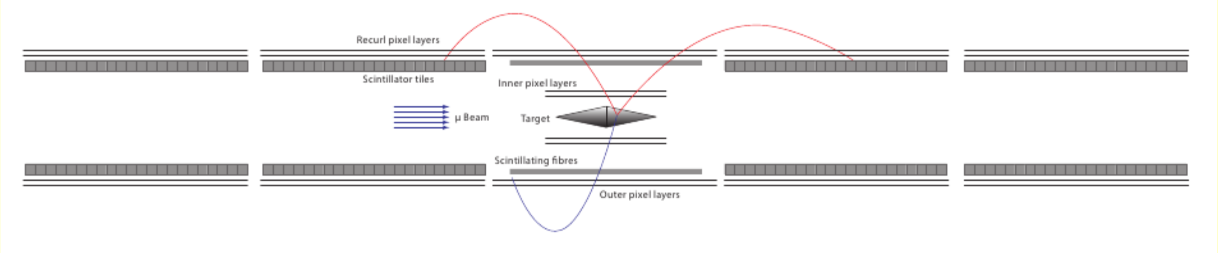
only central Pixel

Phase IB:
rate ~ 10^8 muons/s



+ inner recurl stations
+ time of flight system

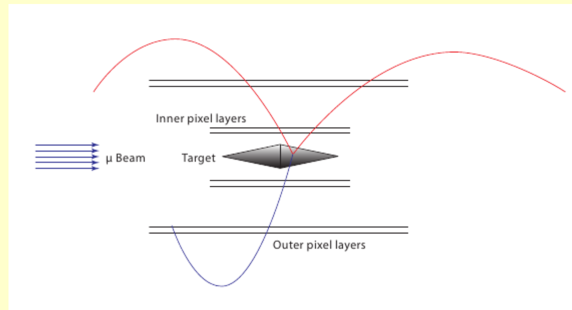
Phase II:
rate ~ 10^9 muons/s



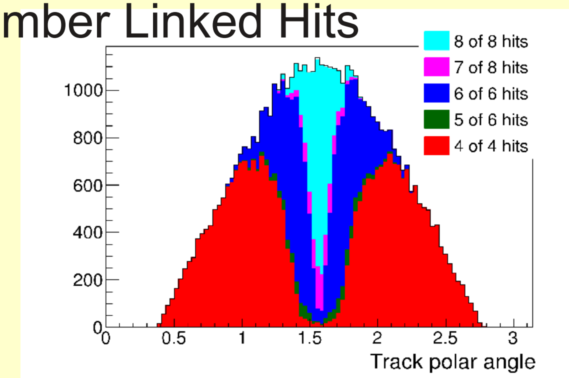
+ outer recurl stations
+ outer tiles

3D Track Reconstruction

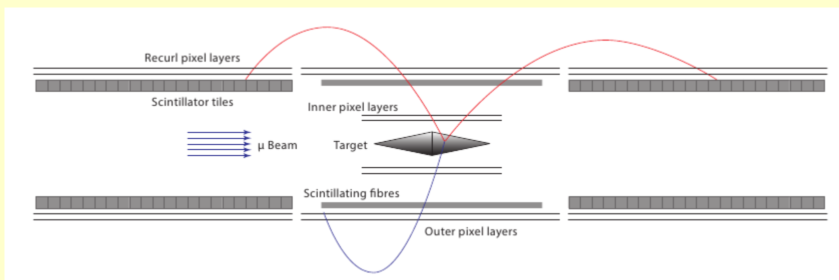
Phase IA:
rate ≤ 10^7 muons/s

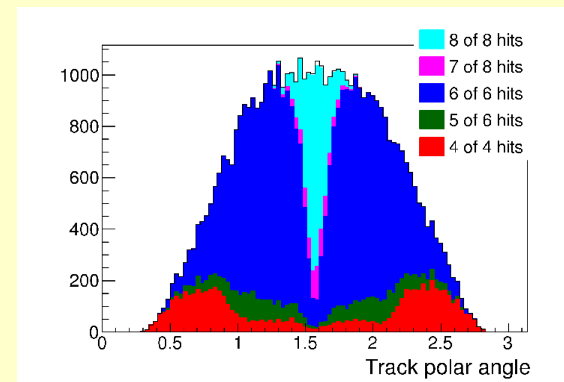


Number Linked Hits

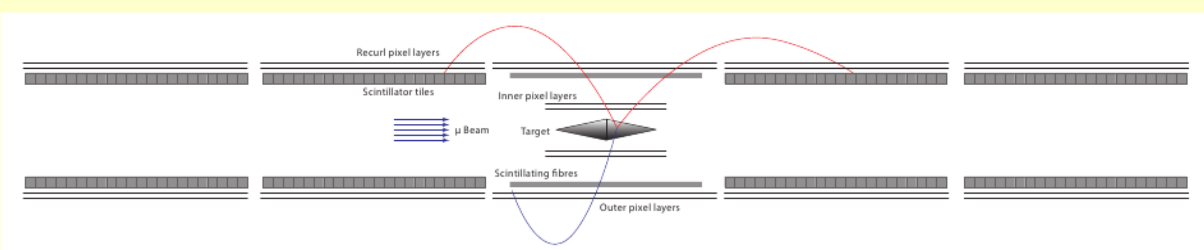


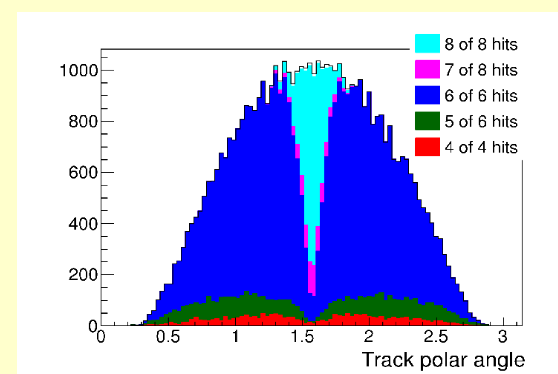
Phase IB:
rate ~ 10^8 muons/s





Phase II:
rate ~ 10^9 muons/s



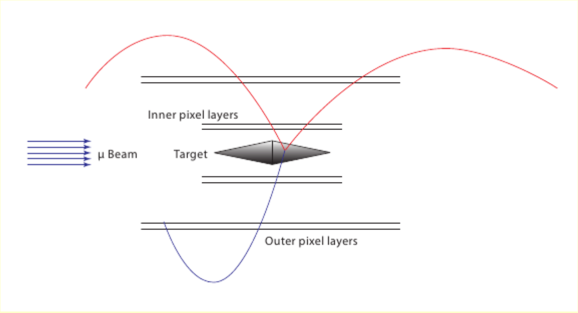


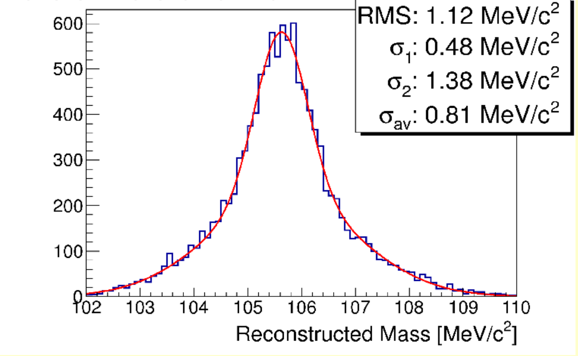
Invariant Mass Resolution of Signal

mass resolution

Phase IA:

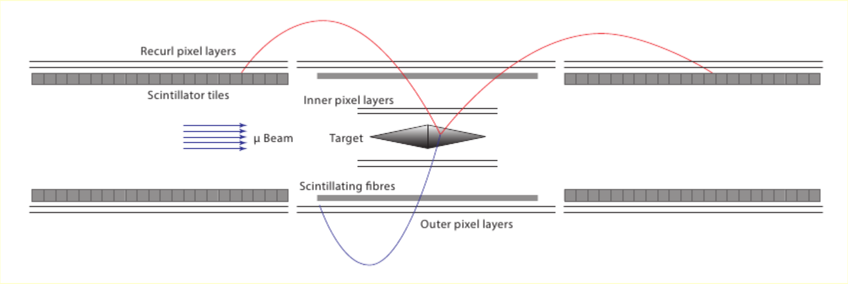
rate ~ 2 · 10^7 muons/s

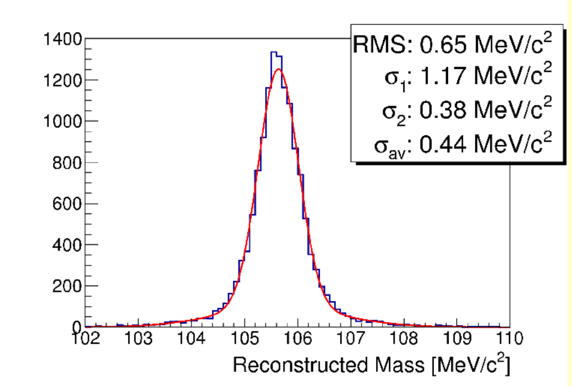




Phase IB:

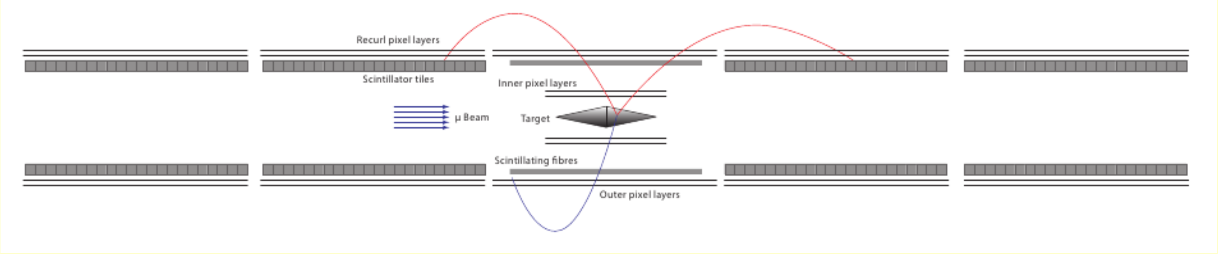
rate ~ 2 · 10^8 muons/s

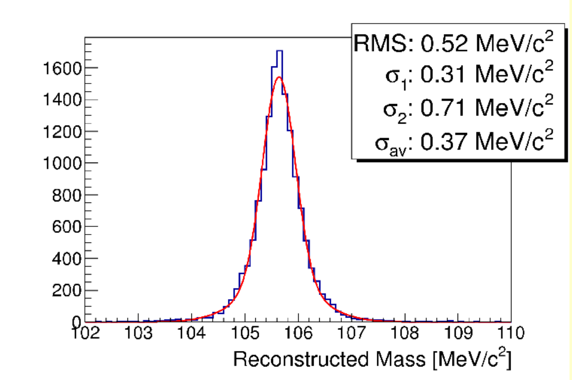




Phase II:

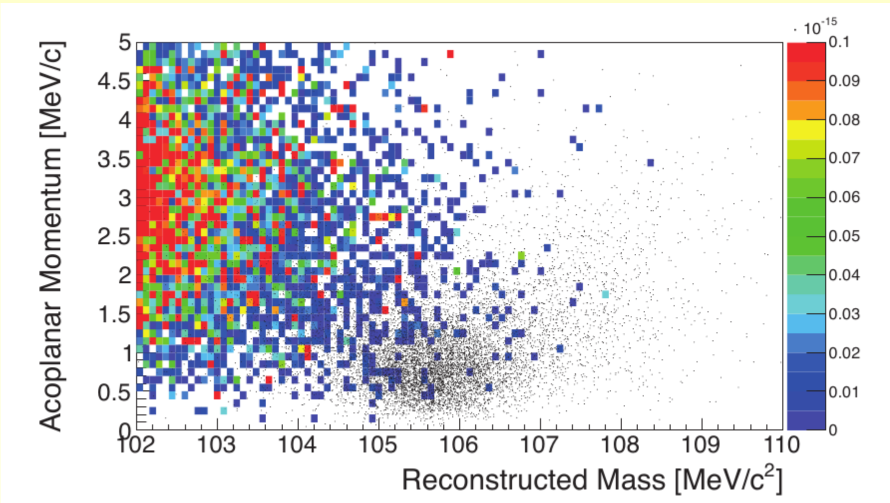
rate ~ 2 · 10^9 muons/s



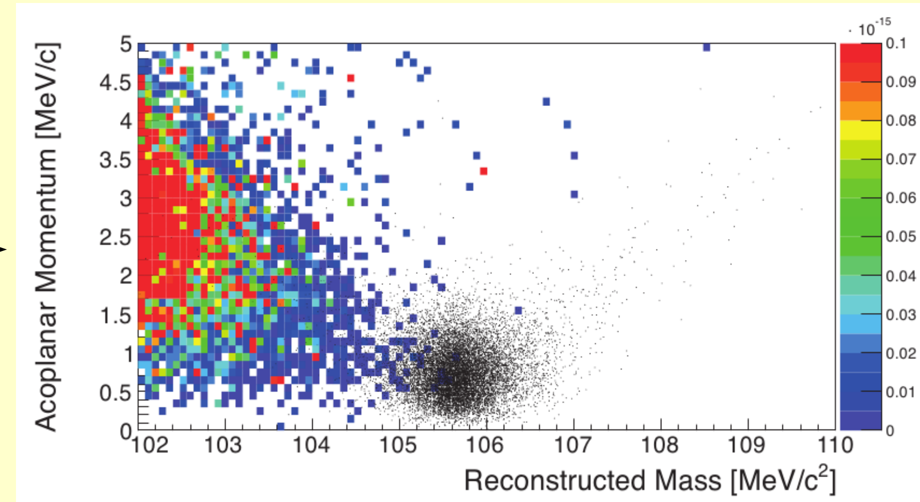


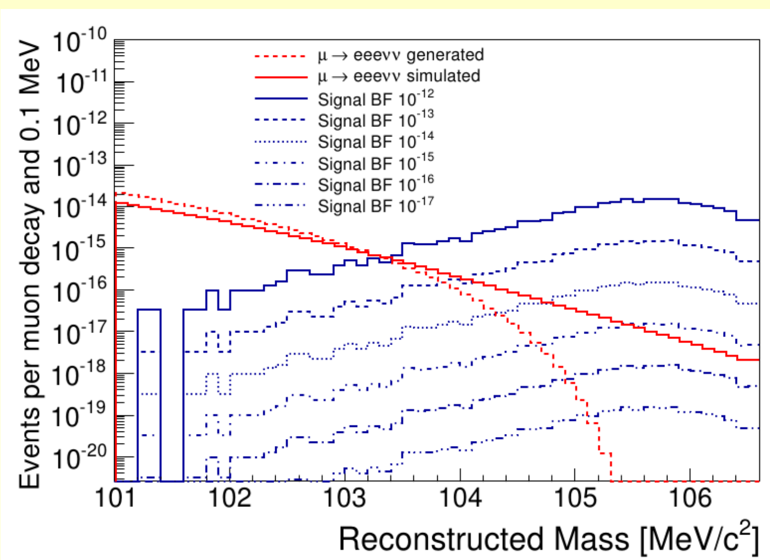
Sensitivity Study

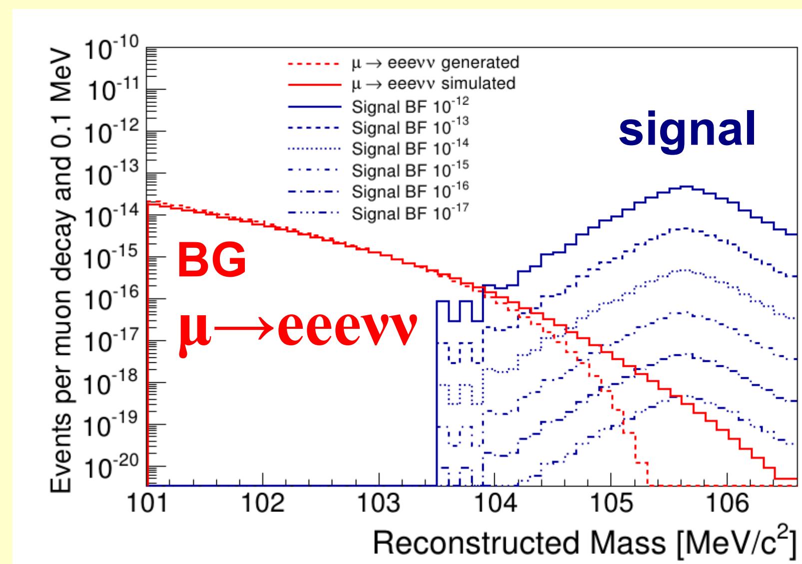
Phase IA: rate ≤ $2 \cdot 10^7$ muons/s



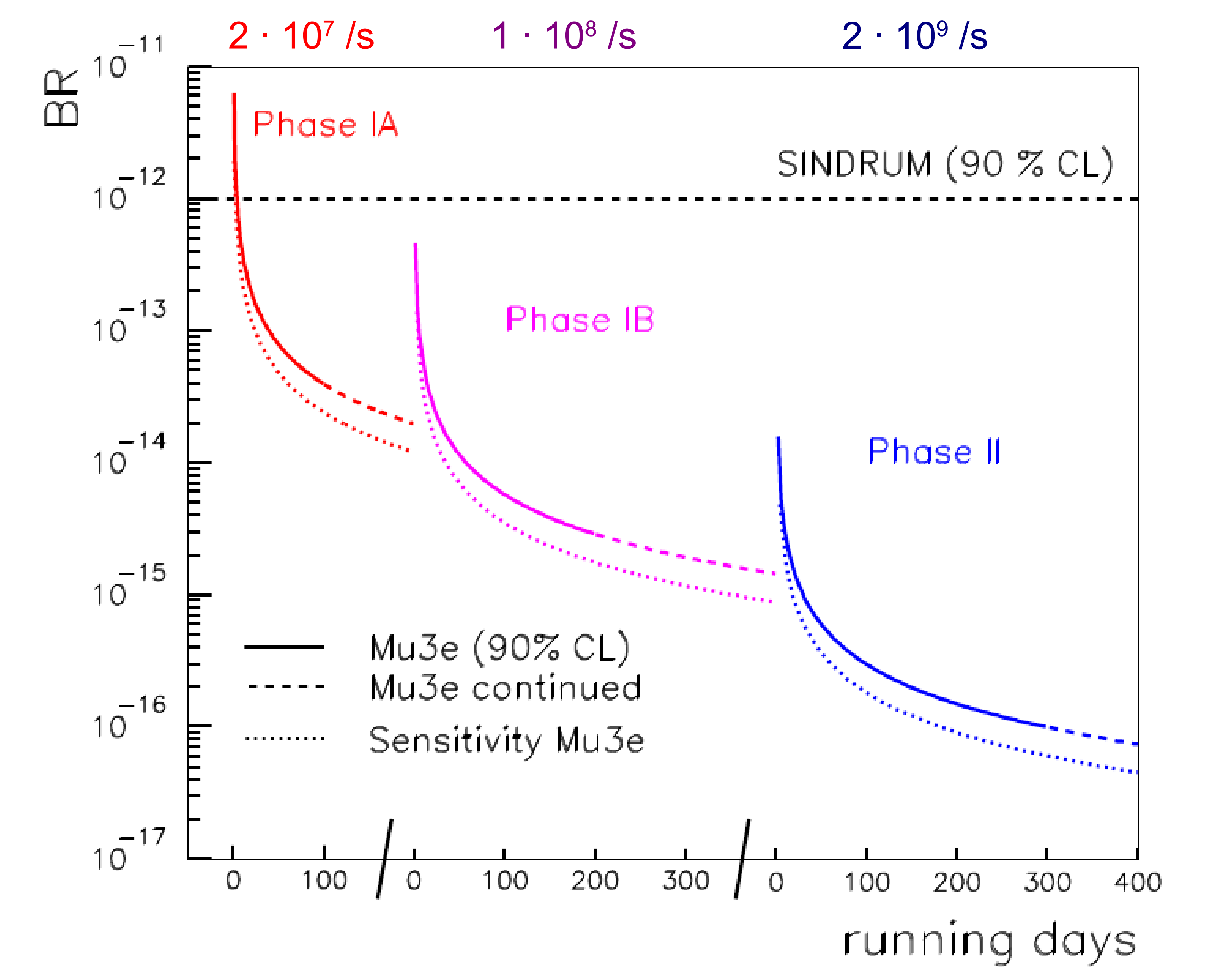
Phase II: rate ~ $2 \cdot 10^9$ muons/s



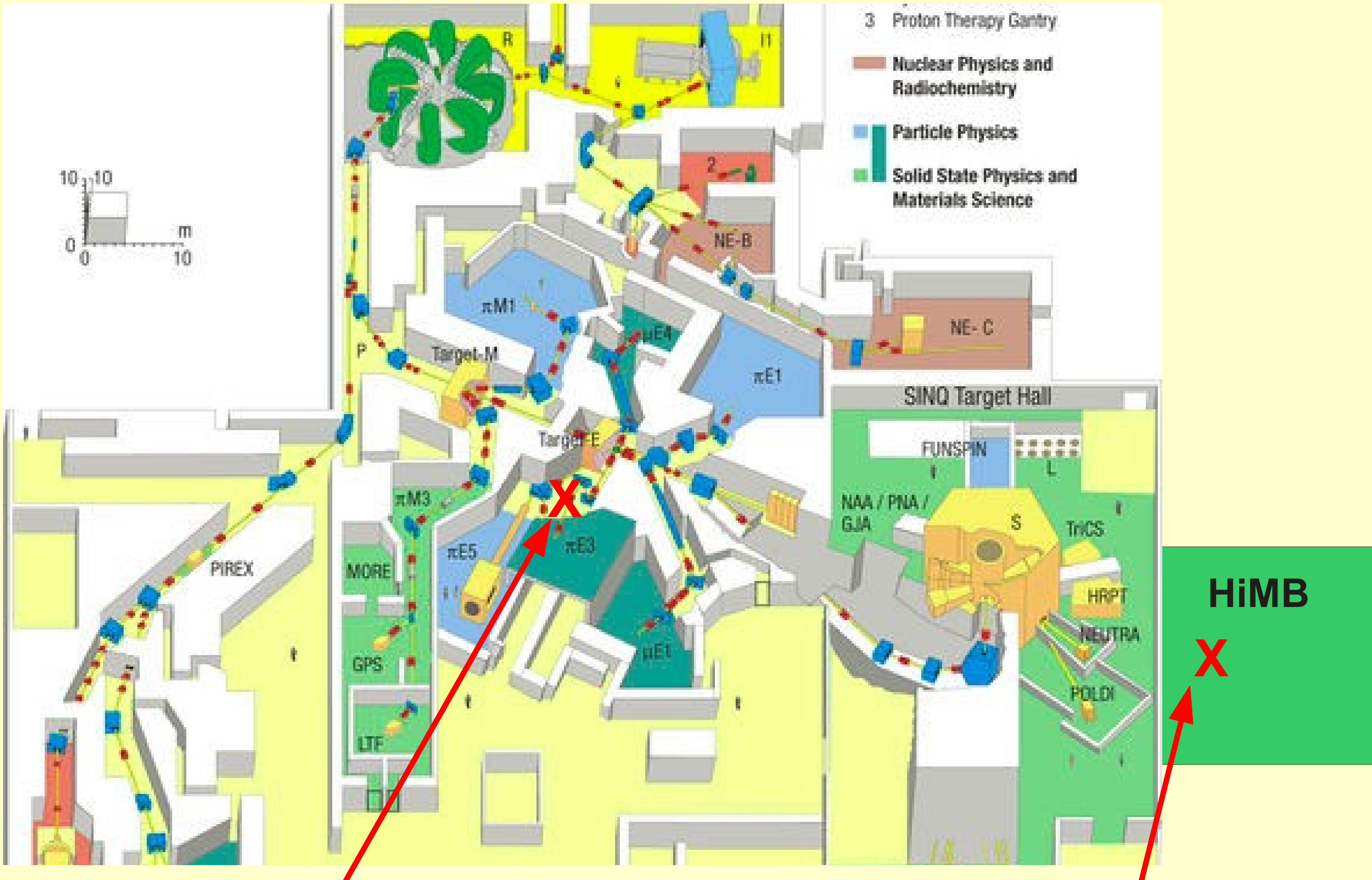




Sensitivity Projection



PSI Facility for Mu3e

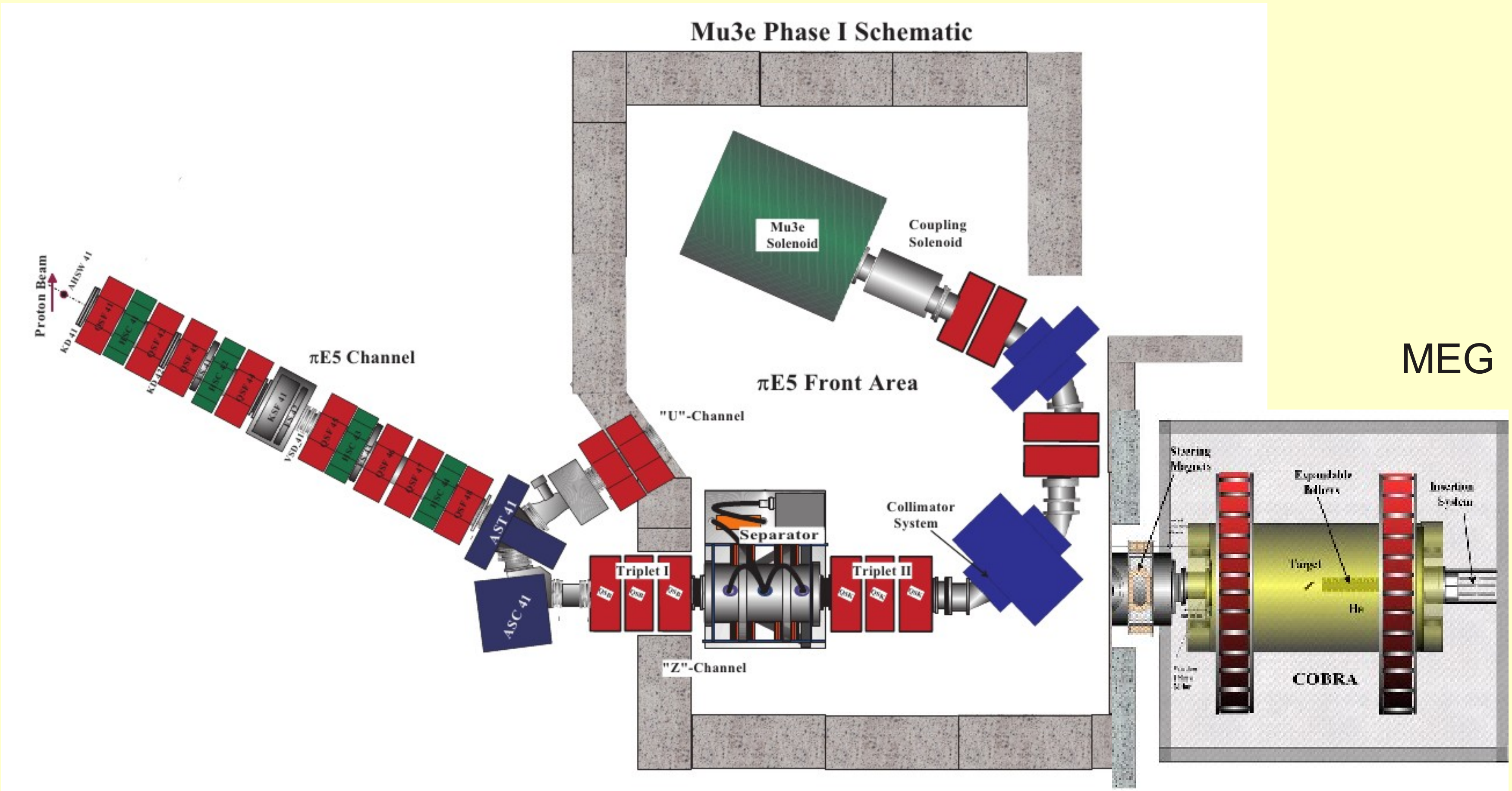


Phase I (2015+): ~**10^8** muons/s

Phase II (>2017): **>10^9** muons/s

πe5 Beamline (Phase I)

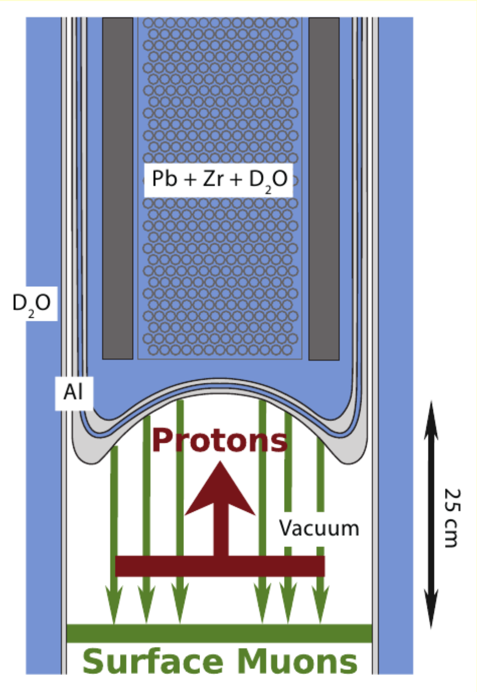
MEG and Mu3e could co-exist if MEG is to be upgraded

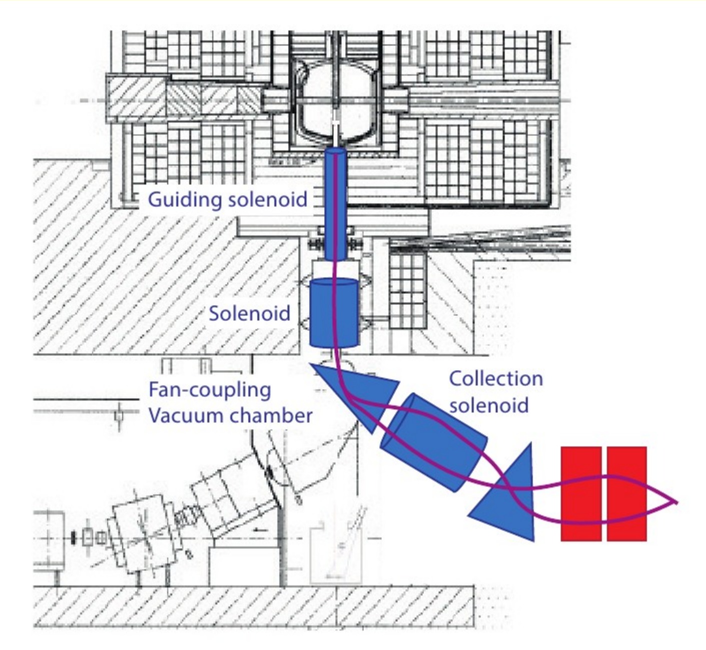


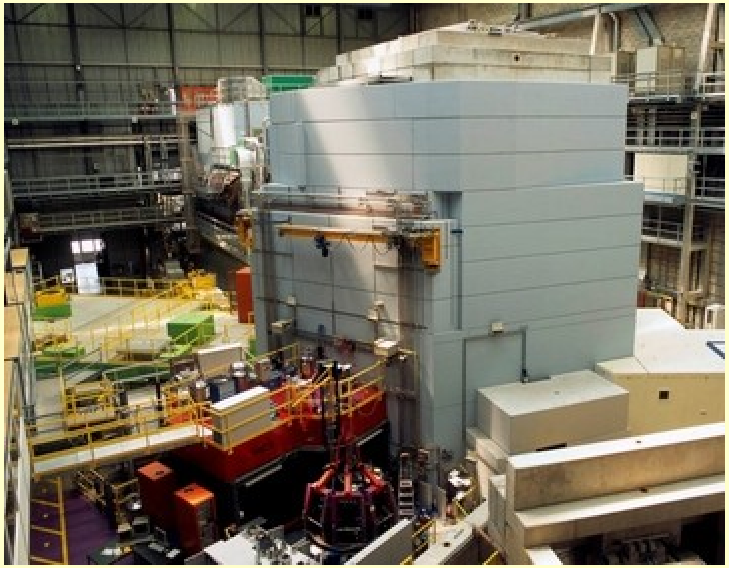
- muon rates of **1.4 · 10⁸/s** achieved in past
- rate of **10⁸/s** needed to reach **B(μ⁺ →e⁺e⁺e⁻) ~ 2 ·10 ⁻¹⁵** (90%CL) in 3 years

High Intensitiy Muon Beamline (Phase II)

HiMB =High Intensity Muon Beamline



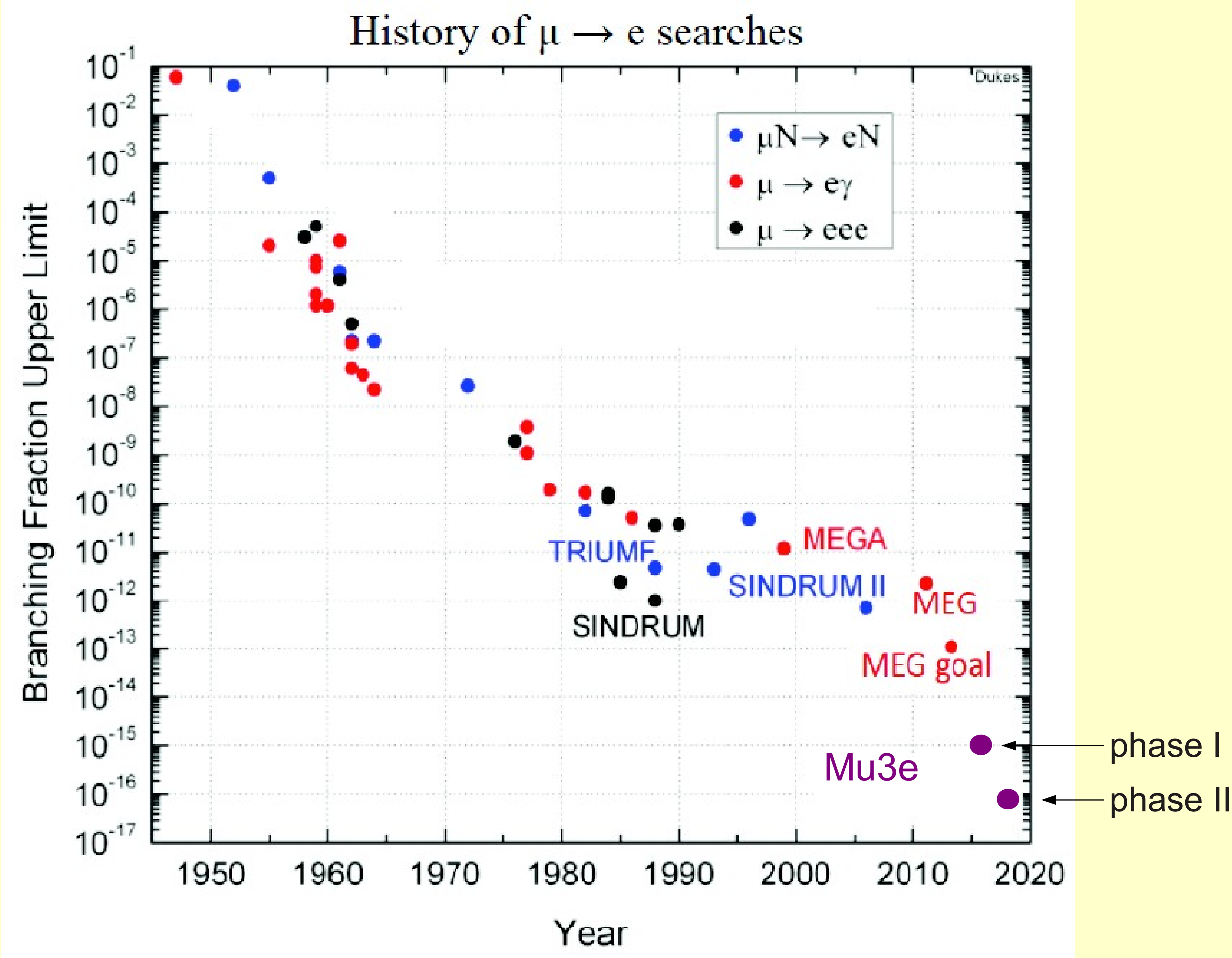




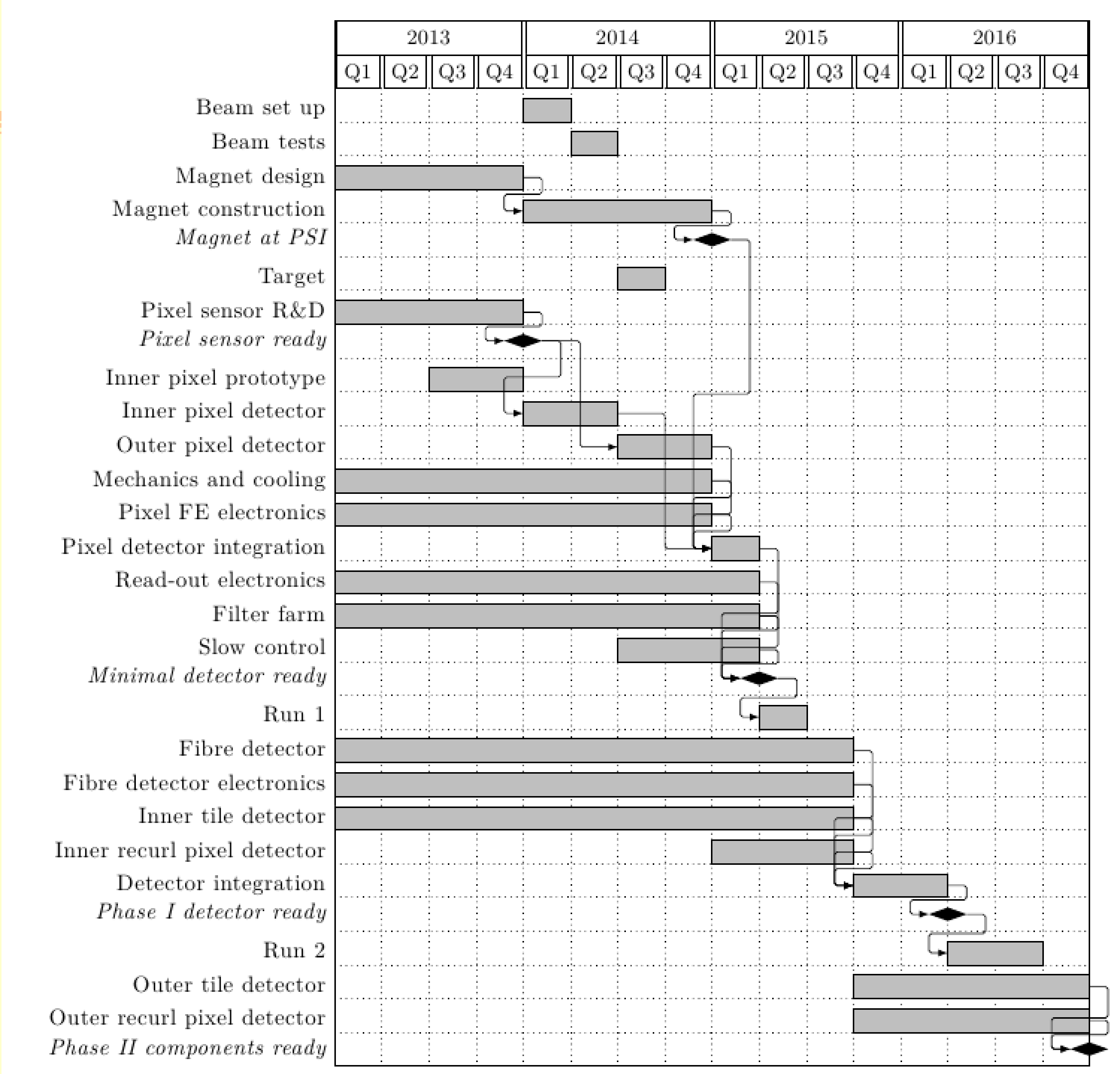
- Muon rates in excess of 10^{10} per second in beam phase acceptance possible
- **$2 \cdot 10^9$** muons/s needed to reach ultimate goal of **$B(\mu^+ \rightarrow e^+e^+e^-) < 10^{-16}$**
- **Not before 2017**

Mu3e Proto-Collaboration

- DPNC Geneva University
- Physics Institute, University Heidelberg
- KIP, University Heidelberg
- ZITI Mannheim, University Heidelberg
- Paul Scherrer Institute
- Physics Institute, University Zurich
- Institute for Particle Physics, ETH Zurich


History of μ → e searches
Dukes
μN→ eN
μ → eγ
μ → eee
Branching Fraction Upper Limit
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
1950
1960
1970
1980
1990
2000
2010
2020
Year
TRIUMF
SINDRUM
SINDRUM II
MEGA
MEG
MEG goal
Mu3e
phase I
phase II

Backup

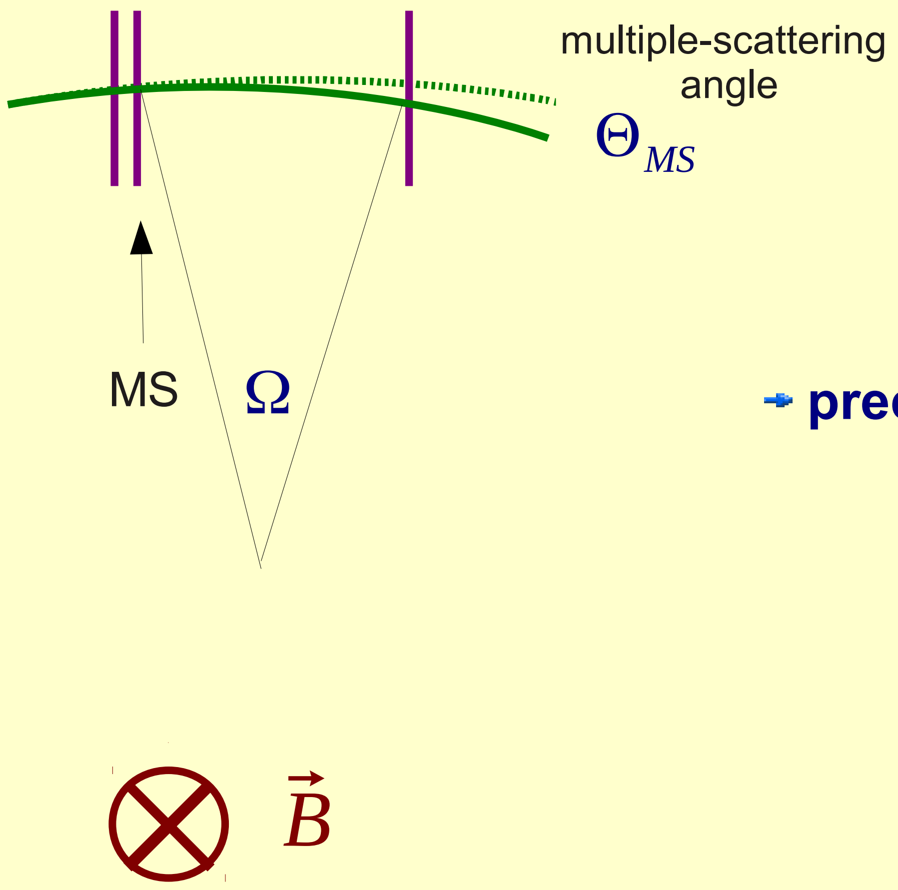

2013
2014
2015
2016
Q1
Q2
Q3
Q4
Beam set up
Beam tests
Magnet design
Magnet construction
Magnet at PSI
Target
Pixel sensor R&D
Pixel sensor ready
Inner pixel prototype
Inner pixel detector
Outer pixel detector
Mechanics and cooling
Pixel FE electronics
Pixel detector integration
Read-out electronics
Filter farm
Slow control
Minimal detector ready
Run 1
Fibre detector
Fibre detector electronics
Inner tile detector
Inner recurl pixel detector
Detector integration
Phase I detector ready
Run 2
Outer tile detector
Outer recurl pixel detector
Phase II components ready

Efficiencies and Backgrounds

	Phase IA	Phase IB	Phase II
Backgrounds:			
Michel	0	$< 2.5 \cdot 10^{-18}$	$5 \cdot 10^{-18}$
$\mu \to ee e\nu\nu$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$1 \cdot 10^{-17}$
$\mu \to eee\nu\nu$ and accidental Michel	0	$< 2.5 \cdot 10^{-21}$	$7.5 \cdot 10^{-18}$
Total Background	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$2.3 \cdot 10^{-17}$
Signal:			
Track reconstruction and selection efficiency	26 %	39 %	38 %
Kinematic cut (2σ)	95 %	95 %	95 %
Vertex efficiency $(2.5\sigma)^2$	98 %	98 %	98 %
Timing efficiency $(2\sigma)^2$	-	90 %	90 %
Total efficiency	24 %	33 %	32 %
Sensitivity:			
Single event sensitivity	$4 \cdot 10^{-16}$	$3 \cdot 10^{-17}$	$7 \cdot 10^{-17}$
muons on target rate (Hz)	$2 \cdot 10^{7}$	$1 \cdot 10^{8}$	$2 \cdot 10^{9}$
running days to reach $1 \cdot 10^{-15}$	2600	350	18
running days to reach $1 \cdot 10^{-16}$	-	3500	180
running days to reach single event sensitivity	6500	11 700	260

Momentum Resolution I

- Momentum resolution given by (linearised):

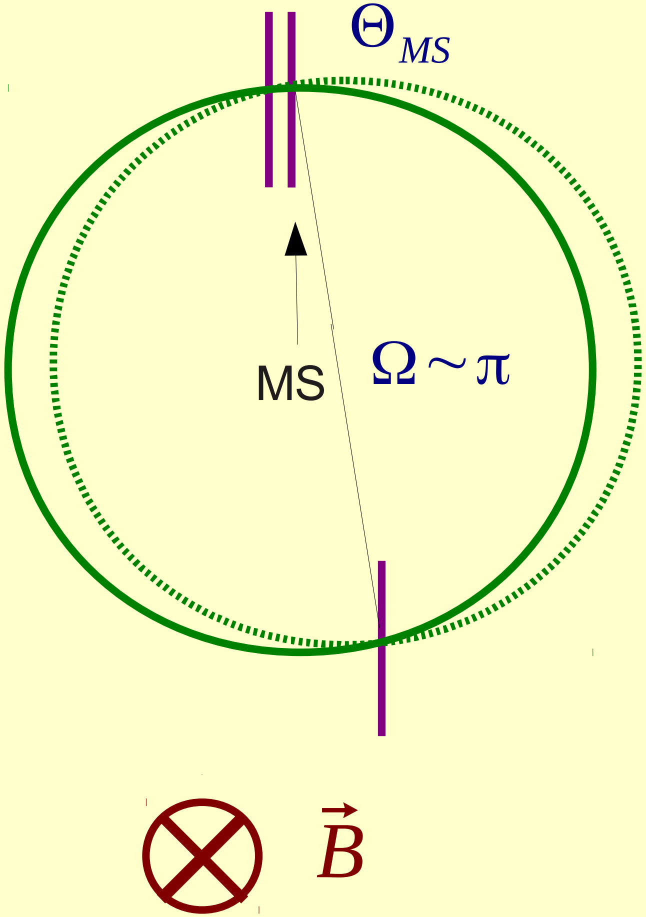


$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$

➡ **precision requires large lever arm (large bending angles Ω)**

Momentum Resolution II

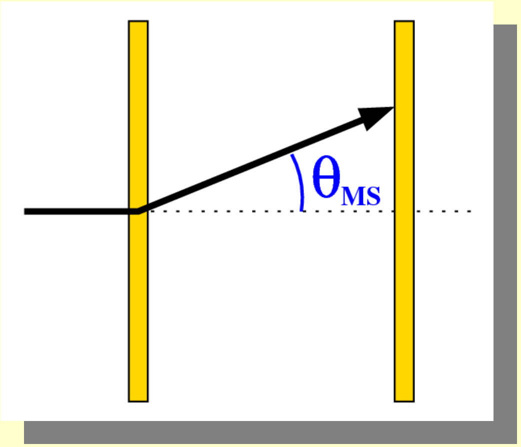
- Momentum resolution for half turns given by:



$$\frac{\sigma_p}{P} \sim O\left(\Theta_{MS}^2\right)$$

- **best precision for half turns**
- **design tracking detector for measuring recurlers**

Multiple Scattering in Silicon



Momentum range p = 15-53 MeV

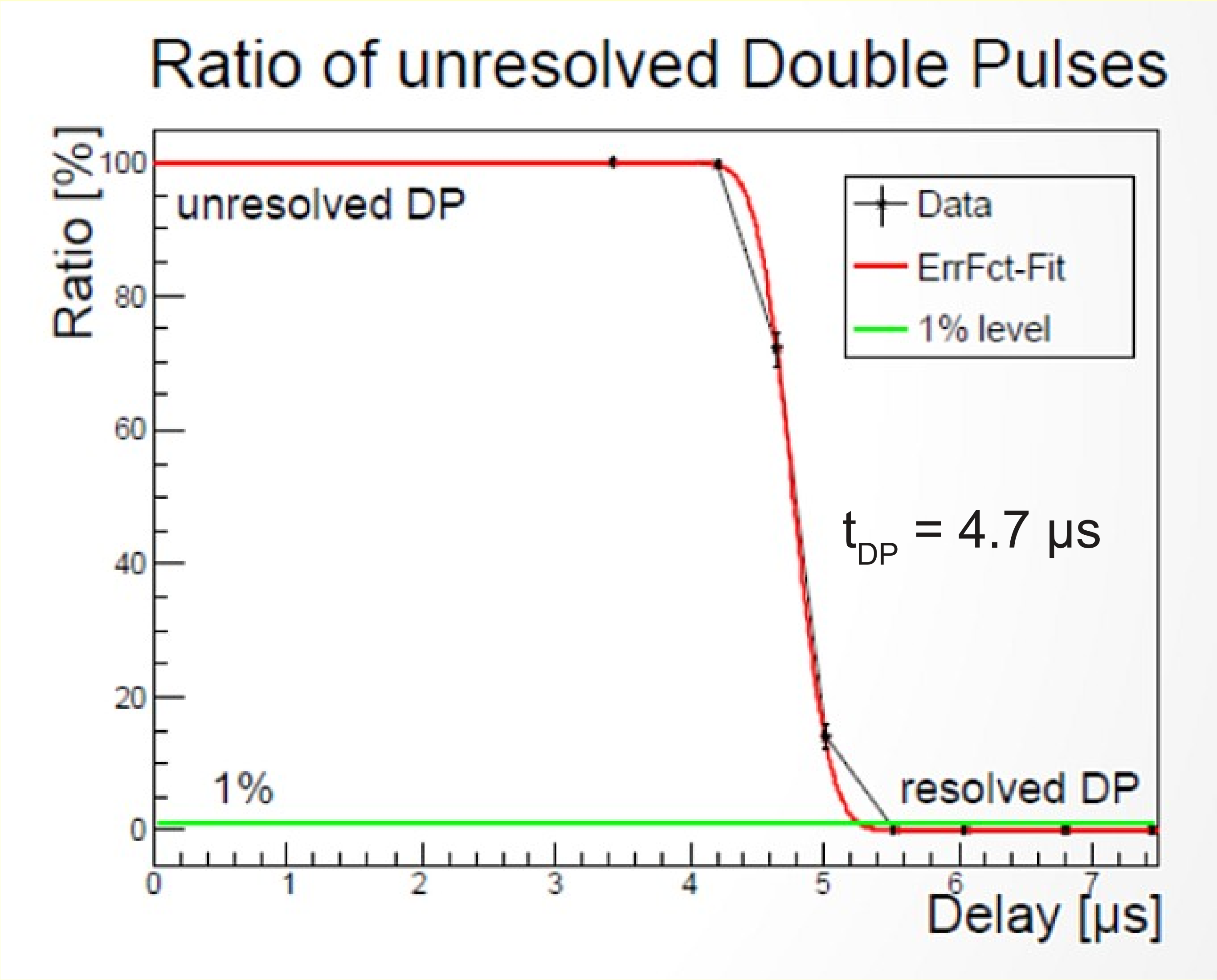
- multiple scattering!

Example: p = 53 MeV/c

- **MEG:** σ_Θ^{MS} = 8 mrad
  - multiple scatt. per layer X/X_0=0.1% → corresponds to 90 µm Silicon
- **µ → eee:** σ_Θ^{MS} = 5 mrad
  - multiple scatt. per layer X/X_0=0.044% → corresponds to 40 µm Silicon

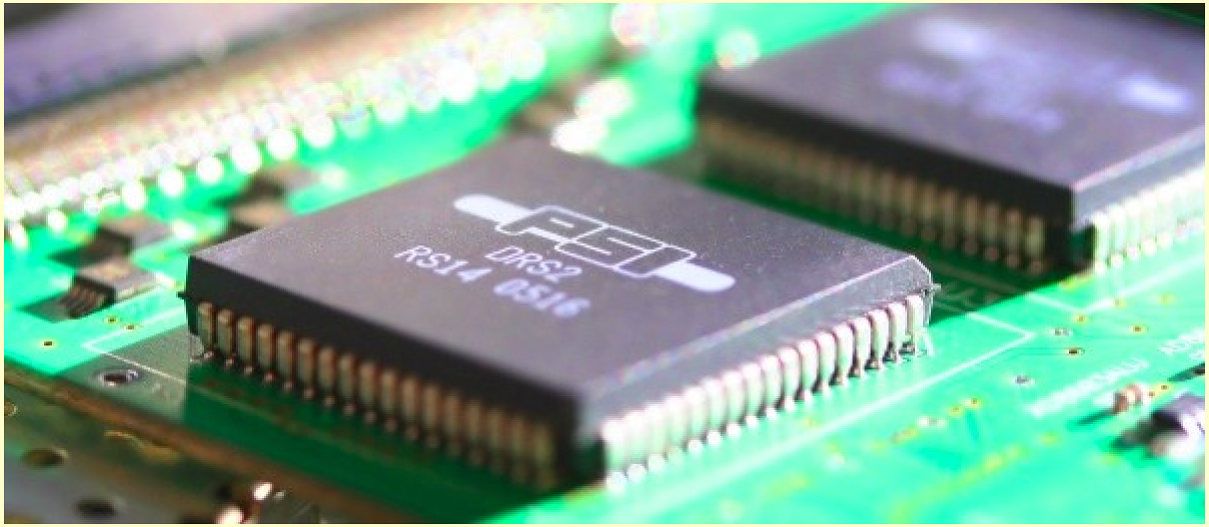
Pixel sensors can be thinned down to 30-50 µm
(examples CMOS MAPS, DEPFET 50 µm)

MuPix2 Tests: Double Pulse Resolution



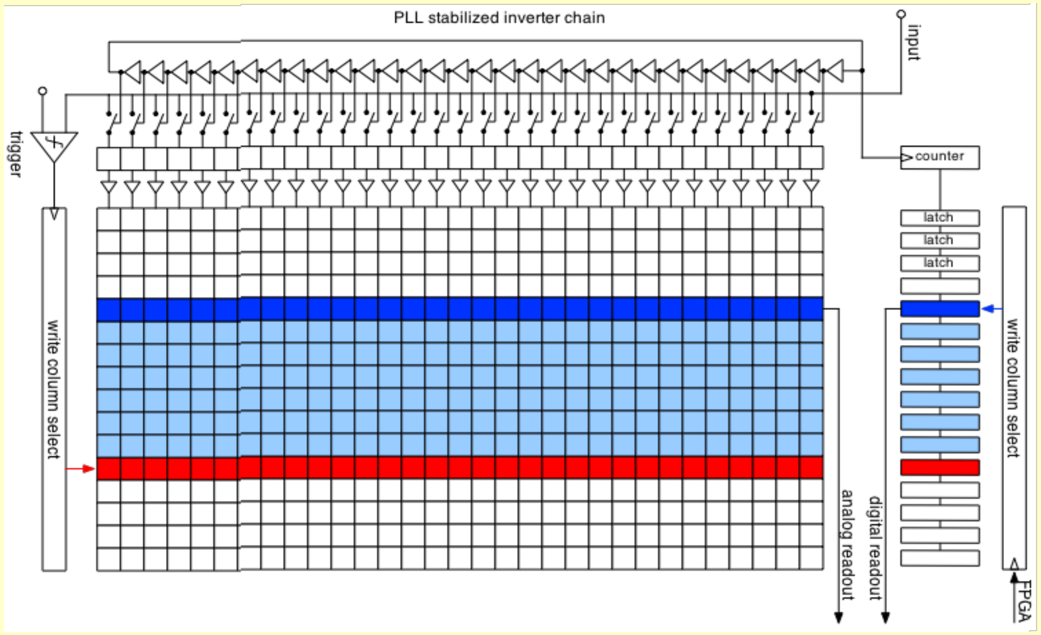
- will improve with MuPix3 chip

ToF Readout + New DRS5 Chip



DRS4 chip (PSI)

- switched capacitor chip
- 8+1 Channels
- 700 MS/s- 5 GS/s



New DRS5 chip (PSI)

- design planned for 2013
- ≥ 2 MHz continuous hit rate
- option for Mu3e - ToF readout

ToF Readout + STIC Chip

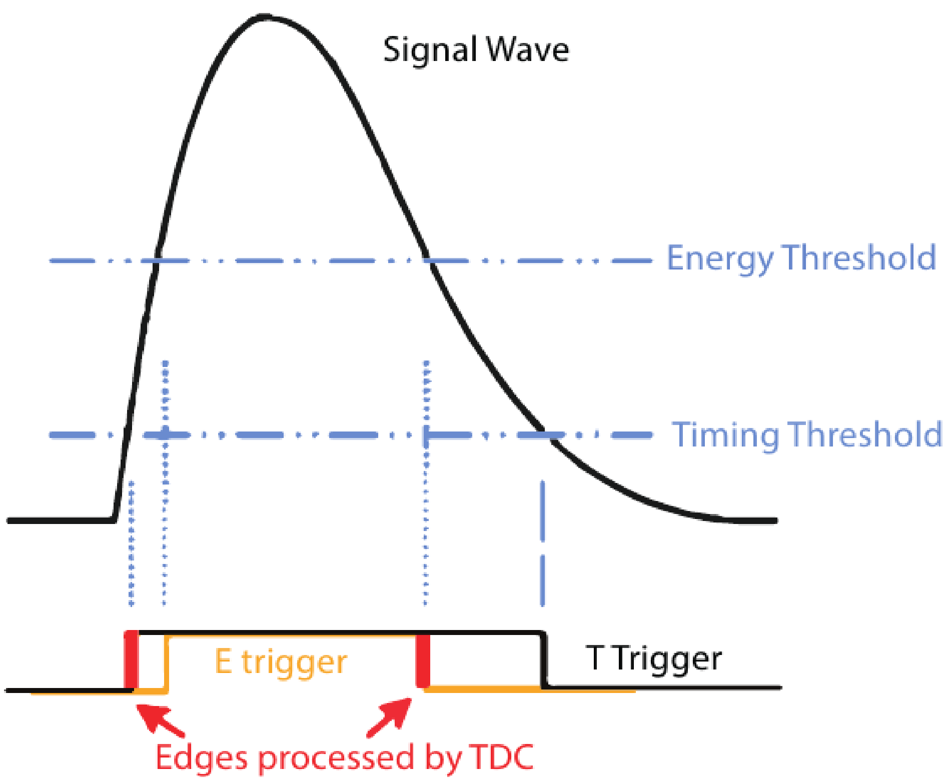


Figure 13.9: Dual threshold discrimination for energy and timing information.

<u>STIC timing chip (KIP Heidelberg)</u>

- 16 channel ASIC
- UMC 180 nm CMOS technology
- for SiPM readout
- tested with MPPC S10362-33-50 SiPM
- time resolution 20ps
- faster version (STIC II) planned

DAQ and Online Filter Farm

Data Acquisition:

- **pixel detector:**
  - number of (zero suppressed) channels ~**275 million**
  - per **50 ns** readout frame **~2000** hits
- **fiber tracker:**
  - number of (zero suppressed) channels about **10k**
- **for muon stop rate of ~$2 \cdot 10^9$ ($2 \cdot 10^8$) muons per second**
  - raw data rate max **~ 250 (25) Gbyte/s** (large but smaller than at LHC)

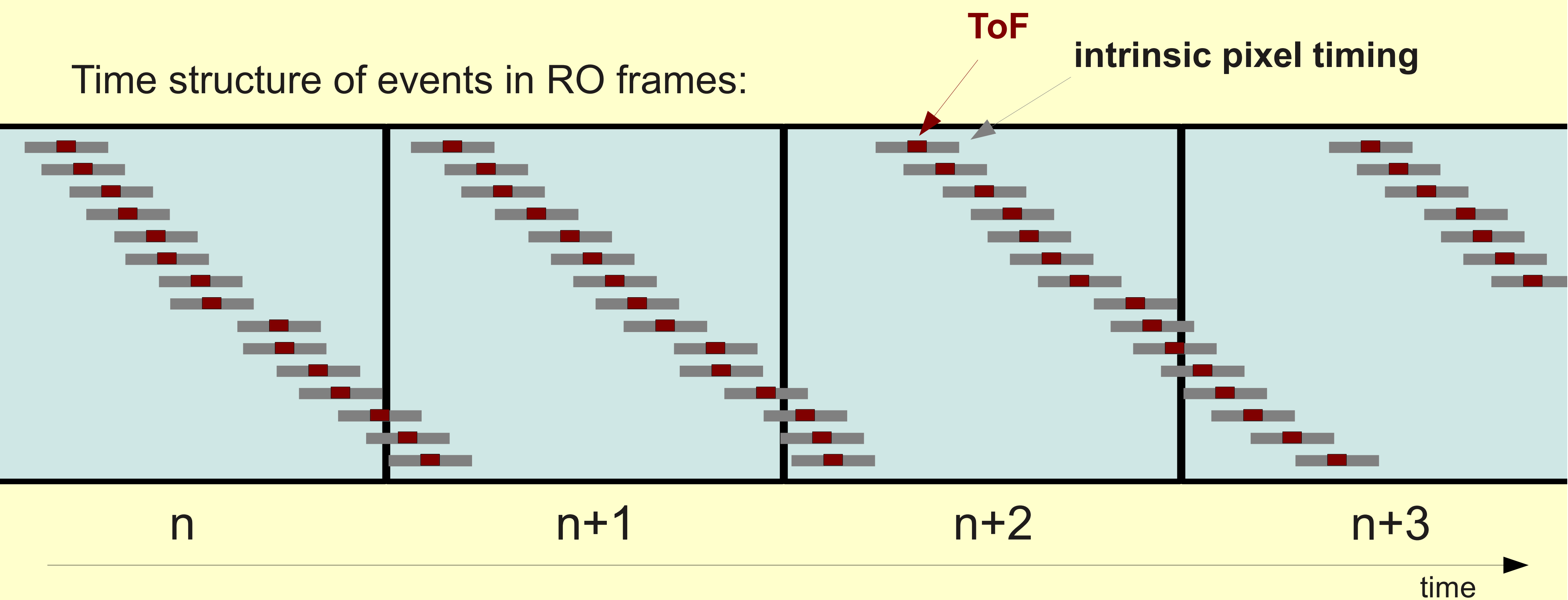
DAQ and Online Filter Farm

- **Online software filter farm**
  - continuous front-end readout (no trigger)
  - FPGAs and Graphical Processor Units (GPUs)
  - online track (event) reconstruction
  - data reduction by factor ~1000
  - on tape ~ 100 Mbyte/s

Readout Frames

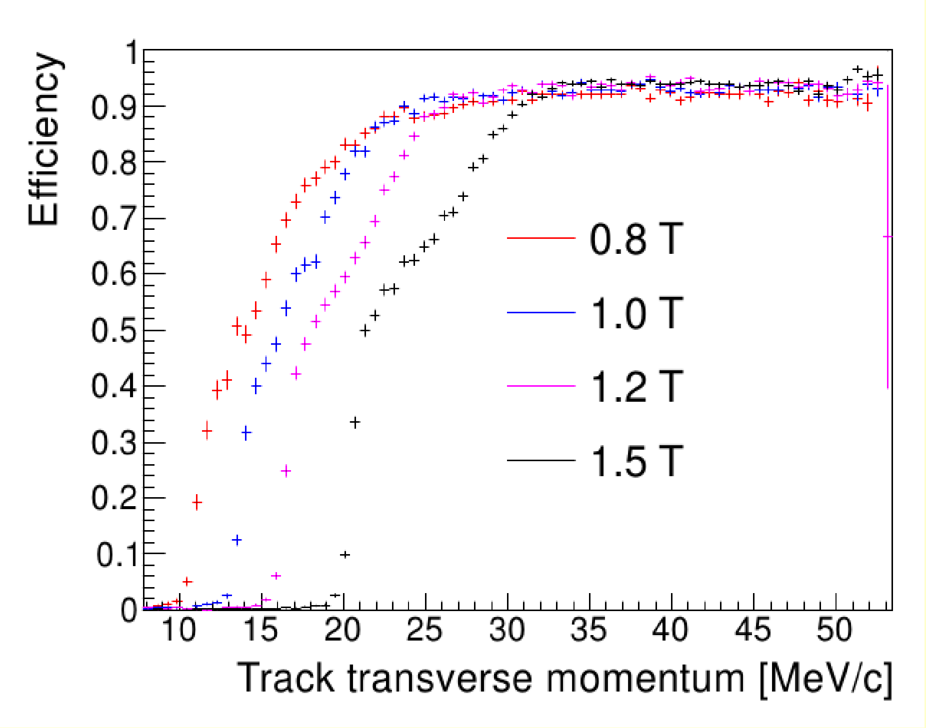
- The pixel detector readout is clocked at 20 MHz (50 ns)
- Intrinsic time resolution in silicon 10-20 ns (to be experimentally verified)
- Precise timing provided by ToF is 0.2-1ns
- Decay positrons spread over up to 3 ns (recurler)

Time structure of events in RO frames:



Magnet

variation of magnetic field



Magnet Design Parameter

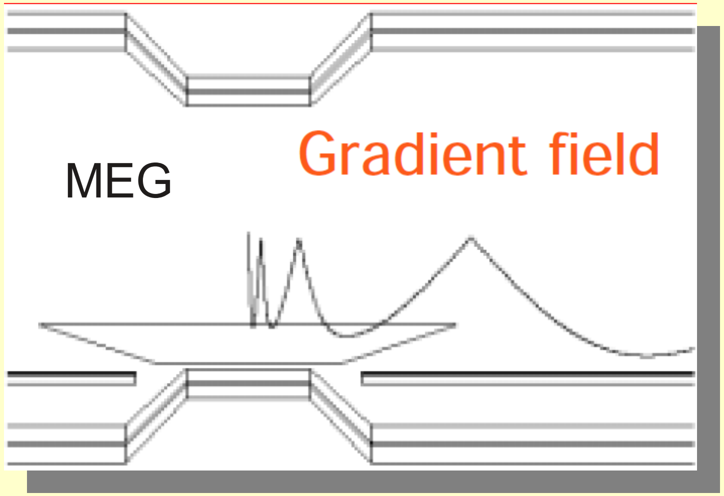
B_{nom} = 1 Tesla

B_{max} = 2 Tesla

Length (inner bore) = 2.5m

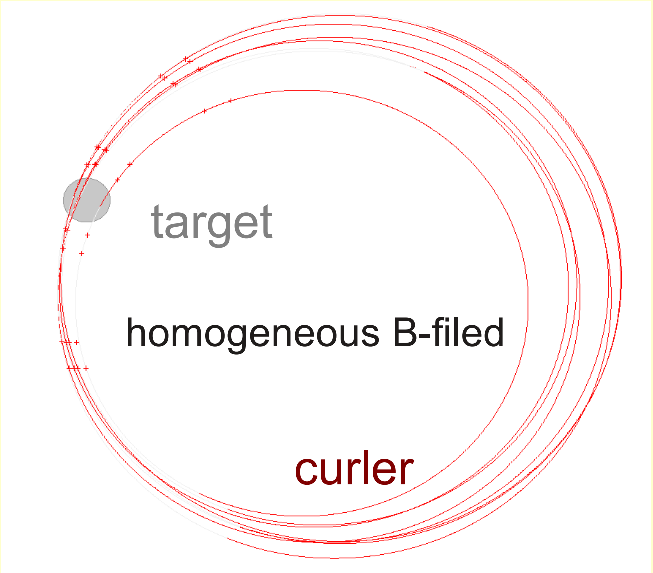
Diameter (inner bore = 1.0 m

Magnet: gradient or no gradient?



Simulation Results for Baseline Design:

- 11 hits per electron gradient field
- 17 hits per electron homogeneous field

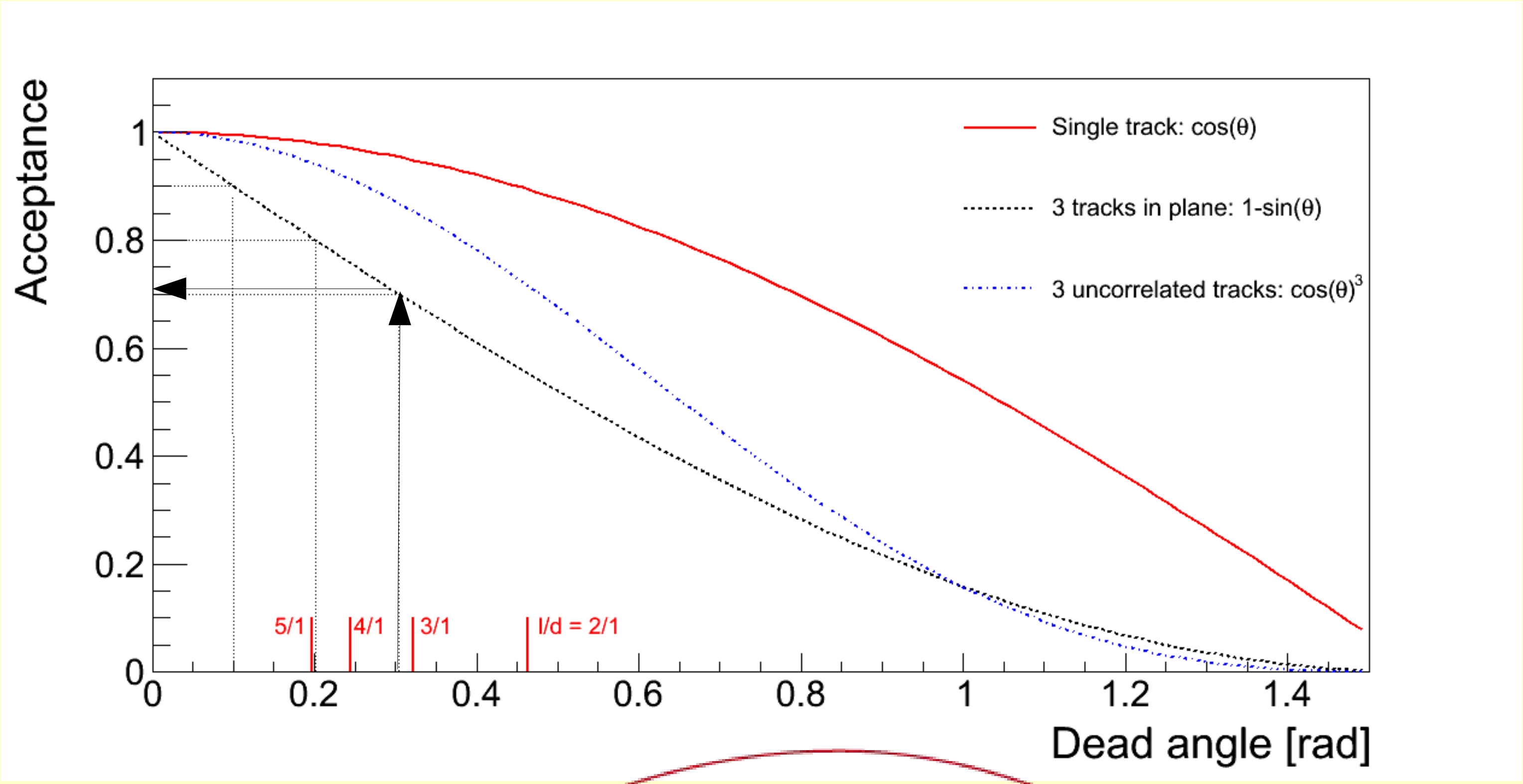


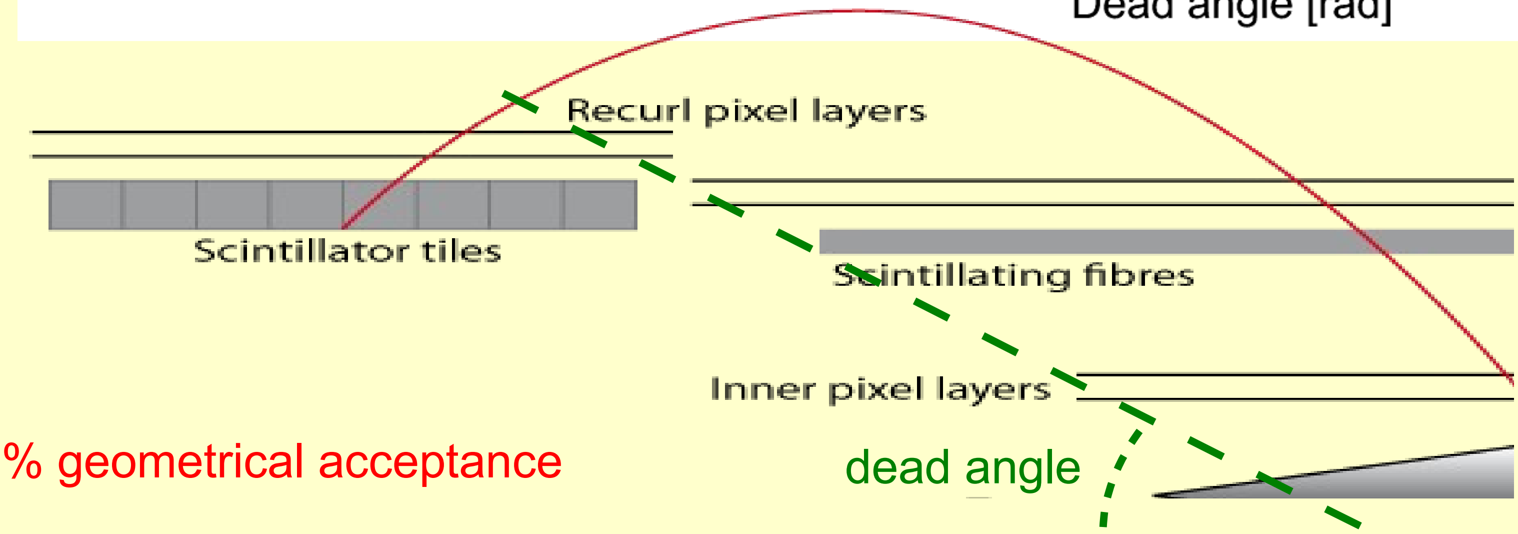
Speed of Track Reconstruction:

- homogeneous field allows for fast non-iterative analytical calculation
- reconstruction speed important for online filtering!

Homogeneous magnetic field of about 1-1.2 Tesla preferred

Geometrical Acceptance





~ 70% geometrical acceptance

Detector Acceptance $\mu^+ \to e^+e^+e^-$

Model Dependence:

$$\frac{dB(\mu \to eee)}{dx_1\, dx_2\, d\cos\theta\, d\phi} = \sum_{k=1}^{5} c_k\, \alpha_k(x_1, x_2)$$

four fermion

photon penguin

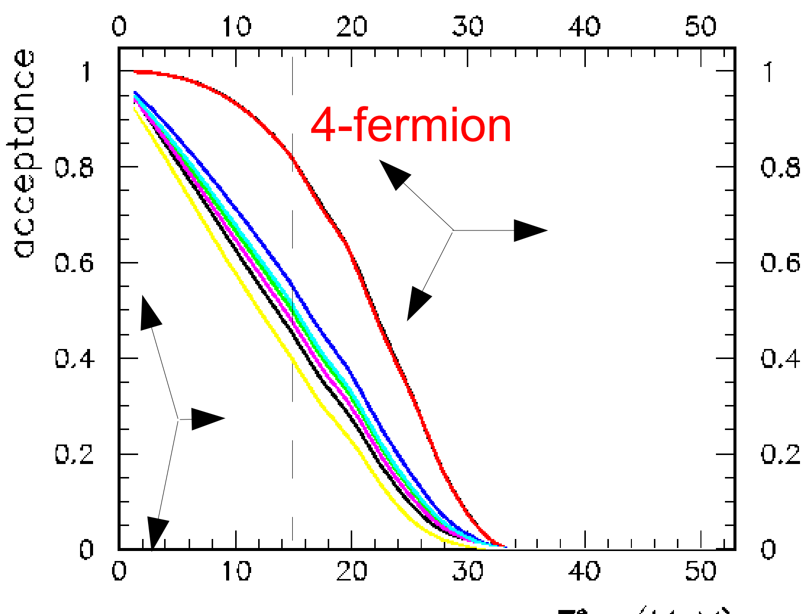
$$c_1 = \frac{g_1^2 + g_2^2}{16} + g_{34}^2$$
$$c_2 = g_{56}^2$$
$$c_3 = e\, A^2$$
$$c_4 = e\, A g_{34}\, \eta$$
$$c_5 = e\, A g_{56}\, \eta'$$

acc ~ 80%

acc ~ 40%

T-odd

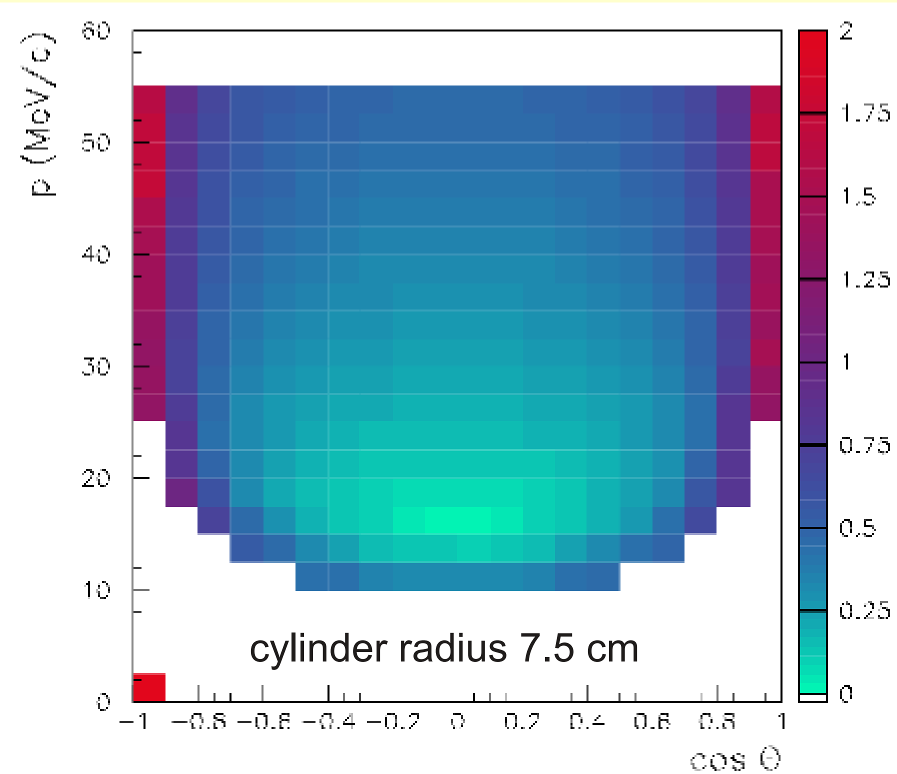
Minimum electron energy:

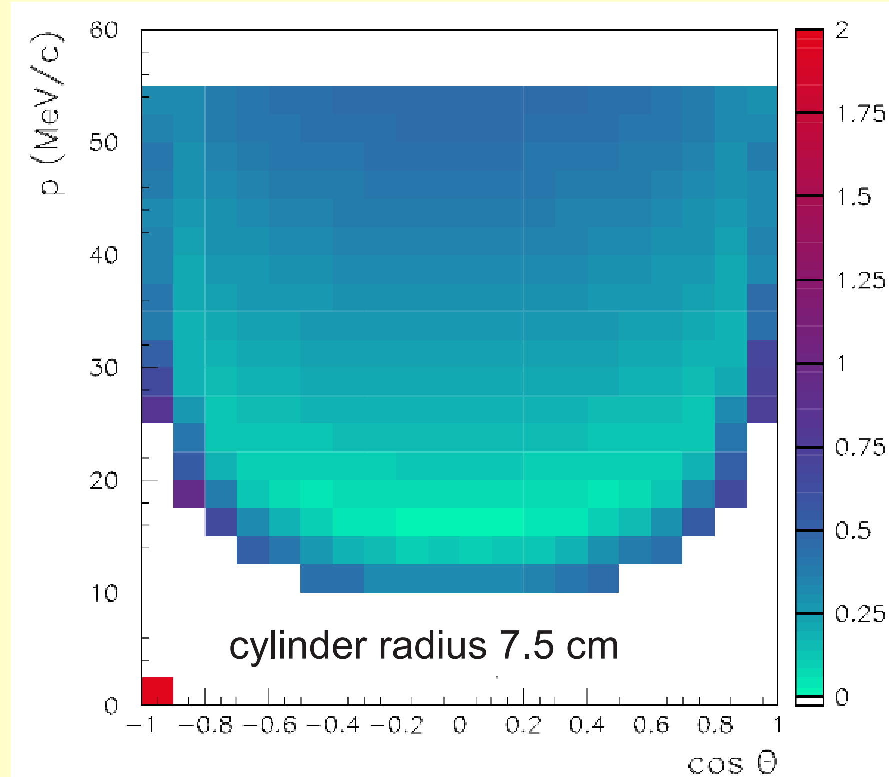


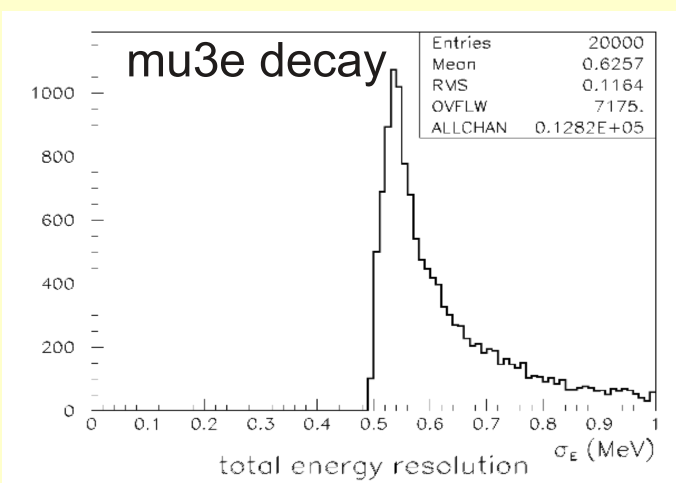
determines acceptance!

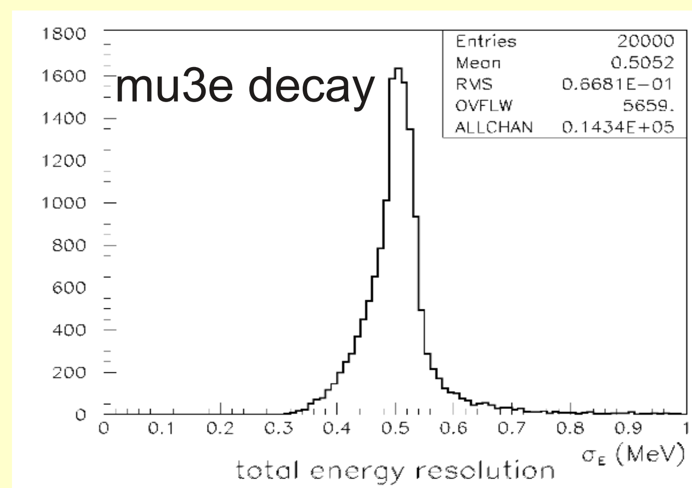
measure momenta
in range: p=15-53 MeV/c

2D versus 3D tracking









Comparison: μ-Decay Experiments

- **Sindrum 1988:**

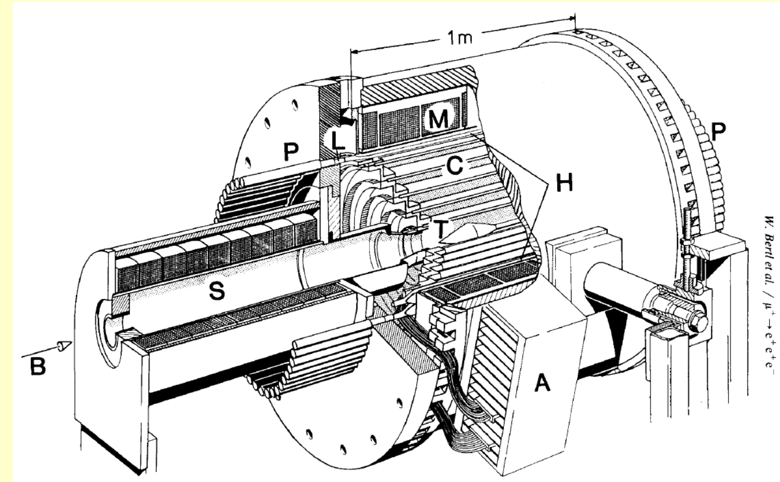
  σ_p/p (50 MeV/c) = 5.1%

  σ_p/p (20 MeV/c) = 3.6%

  σ_θ (20 MeV/c) = 28 mrad

  VTX: σ_d= ~ 1mm

  X0(MWPC) = 0.08% - 0.17% per layer



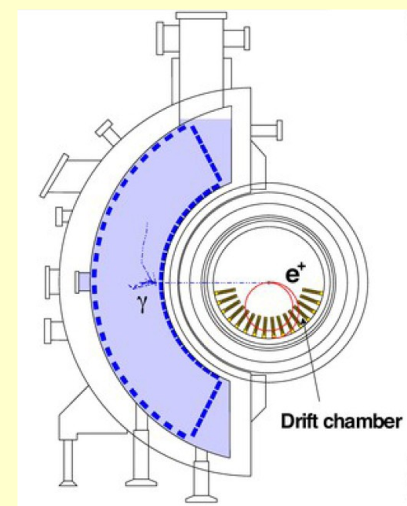
- **MEG 2010 (preliminary):**

  σ_p/p (53 MeV/c) = 0.7 %

  σ_Φ (53 MeV/c) = 8 mrad

  σ_θ (53 MeV/c) = 8 mrad

  VTX: σ_R=1.4 mm, σ_z=2.5 mm



➔ **Aim for similar or better angular and momentum resolutions, high rates and better vertex resolution ~ 150 μm (combinatorial BG)**

Comparison of LFV Experiments

LFV process	Experiment	Future limits	Year (expected)
$\mathrm{BR}(\mu \to e\gamma)$	MEG [8]	$\mathcal{O}(10^{-13})$	~ 2013
	Project X [55]	$\mathcal{O}(10^{-15})$	> 2021
$\mathrm{BR}(\mu \to eee)$	Mu3e [56]	$\mathcal{O}(10^{-15})$	~ 2017
	"	$\mathcal{O}(10^{-16})$	> 2017
	MUSIC [57]	$\mathcal{O}(10^{-16})$	~ 2017
	Project X [55]	$\mathcal{O}(10^{-17})$	> 2021
$\mathrm{CR}(\mu \to e)$	COMET [57]	$\mathcal{O}(10^{-17})$	~ 2017
	Mu2e [58]	$\mathcal{O}(10^{-17})$	~ 2020
	PRISM/PRIME [57, 59]	$\mathcal{O}(10^{-18})$	~ 2020
	Project X [55]	$\mathcal{O}(10^{-19})$	> 2021
$\mathrm{BR}(\tau \to \mu\gamma)$	Belle II [60]	$\mathcal{O}(10^{-8})$	> 2020
$\mathrm{BR}(\tau \to \mu\mu\mu)$	Belle II [60]	$\mathcal{O}(10^{-10})$	> 2020
$\mathrm{BR}(\tau \to e\gamma)$	Super B [45]	$\mathcal{O}(10^{-9})$	> 2020
$\mathrm{BR}(\tau \to \mu\gamma)$	Super B [45]	$\mathcal{O}(10^{-9})$	> 2020
$\mathrm{BR}(\tau \to \mu\mu\mu)$	Super B [45]	$\mathcal{O}(10^{-10})$	> 2020

from Calibbi et al. 2012

Higgs-mediated LFV Yukawa Couplings

Harnik, Kopp, Zupan arXiv:1209.1397